WOODHEAD PUBLISHING SERIES IN TEXTILES

Handbook of medical textiles

Edited by V. T. Bartels

The Textile Institute

WP
WOODHEAD PUBLISHING

Handbook of medical textiles

© Woodhead Publishing Limited, 2011

The Textile Institute and Woodhead Publishing

The Textile Institute is a unique organisation in textiles, clothing and footwear. Incorporated in England by a Royal Charter granted in 1925, the Institute has individual and corporate members in over 90 countries. The aim of the Institute is to facilitate learning, recognise achievement, reward excellence and disseminate information within the global textiles, clothing and footwear industries.

Historically, The Textile Institute has published books of interest to its members and the textile industry. To maintain this policy, the Institute has entered into partnership with Woodhead Publishing Limited to ensure that Institute members and the textile industry continue to have access to high calibre titles on textile science and technology.

Most Woodhead titles on textiles are now published in collaboration with The Textile Institute. Through this arrangement, the Institute provides an Editorial Board which advises Woodhead on appropriate titles for future publication and suggests possible editors and authors for these books. Each book published under this arrangement carries the Institute's logo.

Woodhead books published in collaboration with The Textile Institute are offered to Textile Institute members at a substantial discount. These books, together with those published by The Textile Institute that are still in print, are offered on the Woodhead web site at: www.woodheadpublishing.com. Textile Institute books still in print are also available directly from the Institute's website at: www.textileinstitutebooks.com.

A list of Woodhead books on textile science and technology, most of which have been published in collaboration with The Textile Institute, can be found towards the end of the contents pages.

© Woodhead Publishing Limited, 2011

Woodhead Publishing Series in Textiles: Number 100

Handbook of medical textiles

Edited by
V. T. Bartels

The Textile Institute

Oxford Cambridge Philadelphia New Delhi

© Woodhead Publishing Limited, 2011

Published by Woodhead Publishing Limited in association with The Textile Institute
Woodhead Publishing Limited,
80 High Street, Sawston, Cambridge CB22 3HJ, UK
www.woodheadpublishing.com

Woodhead Publishing, 1518 Walnut Street, Suite 1100, Philadelphia, PA 19102-3406, USA

Woodhead Publishing India Private Limited, G-2, Vardaan House, 7/28 Ansari Road,
Daryaganj, New Delhi – 110002, India
www.woodheadpublishingindia.com

First published 2011, Woodhead Publishing Limited
© Woodhead Publishing Limited, 2011
The authors have asserted their moral rights.

This book contains information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission, and sources are indicated. Reasonable efforts have been made to publish reliable data and information, but the authors and the publishers cannot assume responsibility for the validity of all materials. Neither the authors nor the publishers, nor anyone else associated with this publication, shall be liable for any loss, damage or liability directly or indirectly caused or alleged to be caused by this book.

Neither this book nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, microfilming and recording, or by any information storage or retrieval system, without permission in writing from Woodhead Publishing Limited.

The consent of Woodhead Publishing Limited does not extend to copying for general distribution, for promotion, for creating new works, or for resale. Specific permission must be obtained in writing from Woodhead Publishing Limited for such copying.

Trademark notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation, without intent to infringe.

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library.

Library of Congress Control Number: 2011934929

ISBN 978-1-84569-691-7 (print)
ISBN 978-0-85709-369-1 (online)
ISSN 2042-0803 Woodhead Publishing Series in Textiles (print)
ISSN 2042-0811 Woodhead Publishing Series in Textiles (online)

The publisher's policy is to use permanent paper from mills that operate a sustainable forestry policy, and which has been manufactured from pulp which is processed using acid-free and elemental chlorine-free practices. Furthermore, the publisher ensures that the text paper and cover board used have met acceptable environmental accreditation standards.

Typeset by RefineCatch Limited, Bungay, Suffolk
Printed by TJI Digital, Padstow, Cornwall, UK

Cover image © Fotolia

Contents

Contributor contact details *xiii*
Woodhead Publishing Series in Textiles *xvii*
Preface *xxiii*

Part I Types and properties of medical textiles 1

1 Modern textiles and biomaterials for healthcare 3
S. PETRULYTE and D. PETRULIS, Kaunas University of Technology, Lithuania

1.1 Introduction 3
1.2 The role of textile structures and biomaterials in healthcare 4
1.3 Types of textiles and biomaterials for medical applications 5
1.4 Key properties of medical textile products 9
1.5 Contacting behaviour and transmission phenomenon of medical-based textiles 14
1.6 Engineering stability and compactness in medical textile systems 16
1.7 Advanced examples of research and product development 18
1.8 Future of medical textiles and products 22
1.9 Sources of further information and advice 29
1.10 Acknowledgement 29
1.11 References 29

2 Hi-tech textiles for interactive wound therapies 38
S. RAJENDRAN and S. C. ANAND, University of Bolton, UK

2.1 Introduction 38
2.2 Wounds 39
2.3 Wound dressings 43
2.4 Venous leg ulcers and their treatment 52
2.5 Wound dressing structures 67
2.6 Conclusions 74
2.7 References 75

© Woodhead Publishing Limited, 2011

3 Reusable medical textiles 80
H. M. Zins, Howard M. Zins Associates LLC, USA
3.1 Introduction 80
3.2 The role of reusable medical textiles: a historical perspective 80
3.3 Advantages of reusable textiles 81
3.4 Types of reusable textiles used for medical applications 86
3.5 Processing procedures 94
3.6 Healthcare costs 97
3.7 Future trends 100
3.8 Conclusions 102
3.9 References 102

4 Nonwoven materials and technologies for medical applications 106
J. R. Ajmeri and C. Joshi Ajmeri, Sarvajanik College of Engineering and Technology, India
4.1 Introduction 106
4.2 Key issues of nonwovens 107
4.3 Main types of nonwovens and technologies for medical applications 111
4.4 Strengths and limitations of nonwoven materials (NMs) for medical applications 116
4.5 Applications of nonwovens in medicine 117
4.6 Future trends 125
4.7 Sources of further information and advice 126
4.8 References 126

5 Textiles for implants and regenerative medicine 132
M. Doser and H. Planck, German Institutes for Textile and Fiber Research Denkendorf (DITF), Germany
5.1 Introduction 132
5.2 Textiles as implants 133
5.3 Textiles for regenerative medicine 142
5.4 Testing of implants and materials for regenerative medicine 149
5.5 Sources of further information 150
5.6 References 150

6 Textiles with cosmetic effects 153
R. Mathis and A. Mehling, BASF Personal Care and Nutrition GmbH, Germany
6.1 Introduction 153
6.2 Application and release technologies 154
6.3 Functionalities of cosmetotextiles and performance testing 160
6.4 Safety evaluation and other regulatory aspects 169

© Woodhead Publishing Limited, 2011

6.5 Future trends 170
6.6 References 171

7 Drug-releasing textiles 173
U. S. Toti, S. G. Kumbar, C. T. Laurencin, R. Mathew and D. Balasubramaniam, University of Connecticut Health Center, USA

7.1 Introduction 173
7.2 Classification of drug-releasing textiles 175
7.3 Fabrication and characterization 176
7.4 Applications of drug-releasing textiles 184
7.5 Conclusions 189
7.6 Future trends 190
7.7 Acknowledgments 191
7.8 Sources of further information and advice 191
7.9 References 191

8 Medical textiles and thermal comfort 198
G. Song, University of Alberta, Canada, W. Cao, California State University, Northridge, USA and R. M. Cloud, Baylor University, USA

8.1 Fundamentals of thermal comfort 198
8.2 Healthcare workers and patients in the hospital environment 201
8.3 Thermal comfort of medical textiles: surgical gowns 205
8.4 Evaluation and testing of thermal properties for medical textiles 212
8.5 Future trends 214
8.6 Sources of further information and advice 215
8.7 References 215

Part II Textiles and the skin 219

9 Contact sensations of medical textiles on the skin 221
V. T. Bartels, Bartels Scientific Consulting GmbH, Germany

9.1 Introduction 221
9.2 Skin contact sensations 223
9.3 Textile properties influencing skin contact sensations 227
9.4 Examples of applications 236
9.5 Future trends 241
9.6 Conclusions 242
9.7 Sources of further information 243
9.8 Acknowledgment 243
9.9 References 244

© Woodhead Publishing Limited, 2011

10 Mechanical skin irritations due to textiles 248
U. Wollina, Academic Teaching Hospital Dresden-Friedrichstadt, Germany
10.1 Introduction 248
10.2 Human skin 248
10.3 Skin irritation 250
10.4 Skin responses to mechanical forces 251
10.5 Measurement of irritating mechanical factors 254
10.6 Factors causing a textile to be mechanically irritating 258
10.7 References 263

11 Allergies caused by textiles 267
R. Weckmann, Dr Rainer Weckmann Textile Consulting, Germany
11.1 Introduction 267
11.2 Types of allergies 267
11.3 Main types of allergies caused by textiles 268
11.4 Ways to minimise or avoid allergies caused by textiles 270
11.5 Testing for allergy-causing substances 275
11.6 Medical textile applications 277
11.7 Sources of further information and advice 278
11.8 References 278

12 Biofunctional textiles based on cellulose and their approaches for therapy and prevention of atopic eczema 280
U-C. Hipler and C. Wiegand, Friedrich Schiller University of Jena, Germany
12.1 Introduction 280
12.2 The role of microbial infections in atopic dermatitis 281
12.3 Skin barrier function and increased sensitivity to irritants 283
12.4 Lyocell fibers for antimicrobial therapy 284
12.5 SeaCell® textiles for antimicrobial therapy 286
12.6 Future trends and conclusions 289
12.7 References 290

Part III Textiles for hygiene 295

13 Infection prevention and control and the role of medical textiles 297
R. James, University of Nottingham, UK
13.1 Introduction 297
13.2 Superbugs and healthcare-associated infections (HAIs) 303

© Woodhead Publishing Limited, 2011

13.3 Principles and practice of infection prevention and control in hospitals 306
13.4 The role of textiles in infection prevention and control 309
13.5 Future challenges 310
13.6 A holistic approach to preventing infections 312
13.7 Sources of further information 313
13.8 References 313

14 Absorbent products for personal health care and hygiene 316
F. Wiesemann and R. Adam, Procter & Gamble Service GmbH, Germany
14.1 Introduction 316
14.2 Different types of absorbent products for personal health and hygiene 316
14.3 Key issues of absorbent hygiene products 319
14.4 Testing of absorbent hygiene products 325
14.5 Application example: diapers – adapting products from premature babies to toilet training 329
14.6 Future trends 330
14.7 Sources of further information and advice 333
14.8 Acknowledgements 333
14.9 References 333

15 Bio-functional textiles 336
S. Liu, University of Manitoba, Canada and G. Sun, University of California, Davis, USA
15.1 Introduction 336
15.2 Types of bio-functional textiles 336
15.3 Evaluation of bio-functional effects and safety 343
15.4 Applications of bio-functional textiles 344
15.5 Manufacturing of bio-functional textiles 346
15.6 Future trends 353
15.7 Sources of further information 354
15.8 References 354

16 Hospital laundries and their role in medical textiles 360
J. Beringer and J. Kurz, Hohenstein Institutes, Germany
16.1 Introduction 360
16.2 Key issues of hospital laundries 361
16.3 Impact of hospital laundries on the hygiene of medical textiles 369
16.4 Testing and quality control of hygienic properties in hospital laundries 378

© Woodhead Publishing Limited, 2011

16.5 State of the art in hospital laundries 381
16.6 Future trends 382
16.7 Sources of further information and advice 382
16.8 Further reading 382
16.9 Appendix: additional information 383

17 Odour control of medical textiles 387
R. H. McQueen, University of Alberta, Canada
17.1 Introduction 387
17.2 Measurement of odour 388
17.3 Key issues of odour control in medical applications 396
17.4 Control of odour with textiles 401
17.5 Future trends 410
17.6 Acknowledgement 411
17.7 References 411

Part IV Medical textile case studies and applications 417

18 Textiles for medical filters 419
W. Zhong, University of Manitoba, Canada
18.1 Introduction 419
18.2 Key issues of medical filters 419
18.3 Application of hollow fiber bioreactors 423
18.4 Evaluation and characterization of medical filters 425
18.5 Future trends 430
18.6 References 431

19 Textiles for patient heat preservation during operations 434
U. Möhring, D. Schwabe and S. Hanus, Textile Research Institute Thuringia-Vogtlande. V., Germany
19.1 Key issues and importance of preventing cold stress in patients during operations 434
19.2 Main types of textiles used to maintain patient temperature during operations 435
19.3 Applications of textiles in maintaining patient temperature 435
19.4 Future trends 437
19.5 Sources of further information and advice 440
19.6 References 441

© Woodhead Publishing Limited, 2011

20 Evaluation of occupational clothing for surgeons: achieving comfort and avoiding physiological stress through suitable gowns 443
W. Nocker, Consultant, Germany

20.1 Historical background 443
20.2 Surgical gowns 444
20.3 Influences on wear properties 444
20.4 Elements of comfort 447
20.5 Evaluation of parameters relevant for comfortable textiles 447
20.6 Sweating as an effect of physiological stress 448
20.7 Controlled wear tests 451
20.8 Purchasing criteria 456
20.9 Conclusions and recommendations 458
20.10 References 459

21 Occupational clothing for nurses: combining improved comfort with economic efficiency 461
M. Walz, Eschler Textil GmbH, Germany

21.1 Introduction 461
21.2 Materials and methods 463
21.3 Cleanliness 464
21.4 Improving comfort in nurses' occupational clothing 464
21.5 Improving durability of nurses' clothing in industrial laundering processes 468
21.6 Possible savings in resources, washing and drying, durability and nosocomial infections 475
21.7 Applications of knitted microfibre fabrics 476
21.8 Future trends 477
21.9 Sources of further information and advice 479
21.10 Acknowledgement 479
21.11 References 480

22 Medical bandages and stockings with enhanced patient acceptance 481
C. Rotsch, H. Oschatz, D. Schwabe, M. Weiser and U. Möhring, Textile Research Institute Thuringia-Vogtlande., V. Germany

22.1 Introduction 481
22.2 Key issues and the role of medical bandages and stockings 482
22.3 Improving patient acceptance of medical bandages and stockings 492
22.4 Conclusions 500
22.5 References 501

© Woodhead Publishing Limited, 2011

23 Superabsorbents and their medical applications 505
G. Bartkowiak, Central Institute for Labour Protection – National Research Institute, Poland and I. Frydrych, Central Institute for Labour Protection – National Research Institute, Poland and Technical University of Lodz, Poland
23.1 Introduction 505
23.2 Methods of obtaining superabsorbent polymers and their chemical structure 506
23.3 Forms of superabsorbents and their properties 510
23.4 Development stages of superabsorbent materials according to appropriate patents 516
23.5 Applications of superabsorbents in medicine 518
23.6 Applications of superabsorbents in hygiene products and medical textiles 520
23.7 Applications of superabsorbents for comfort improvement 525
23.8 Ergonomic tests 534
23.9 Application of superabsorbent materials in half masks 542
23.10 Conclusions 543
23.11 References 544

24 Nanofibrous textiles in medical applications 547
L. Van der Schueren and K. De Clerck, Ghent University, Belgium
24.1 Introduction 547
24.2 Nanofibrous textiles 547
24.3 Applications of nanofibres in the medical field 551
24.4 Future trends 559
24.5 Sources of further information and advice 560
24.6 References 560

Index *567*

© Woodhead Publishing Limited, 2011

Contributor contact details

(* = main contact)

Editor and Chapter 9

V. T. Bartels
Bartels Scientific Consulting GmbH
Heidestrasse 26
74336 Brackenheim
Germany
E-mail: vt.bartels@bartels-scientific.de

Chapter 1

S. Petrulyte* and D. Petrulis
Department of Textile Technology
Kaunas University of Technology
Studentu 56
LT-51424
Kaunas
Lithuania
E-mail: salvinija.petrulyte@ktu.lt;
donatas.petrulis@ktu.lt

Chapter 2

S. Rajendran* and S. C. Anand
Institute for Materials Research and Innovation
University of Bolton
Bolton
BL3 5AB
UK
E-mail: S.Rajendran@bolton.ac.uk

Chapter 3

H. M. Zins
Howard M. Zins Associates LLC
810 Rotherham Drive
Ballwin
MO 63011
USA
E-mail: hmzins@yahoo.com

Chapter 4

J. R. Ajmeri* and C. Joshi Ajmeri
Department of Textile Technology
Sarvajanik College of Engineering and Technology
Dr R. K. Desai Marg
Athwalines
Surat – 395 001
Gujarat
India
E-mail: jajmeri@hotmail.com

© Woodhead Publishing Limited, 2011

Chapter 5

M. Doser* and H. Planck
Department of Biomedical Engineering
Institute of Textile Technology and Process Engineering (ITV)
German Institutes for Textile and Fiber Research Denkendorf (DITF)
Koerschtalstrasse 26
73770 Denkendorf
Germany
E-mail: Michael.doser@itv-denkendorf.de

Chapter 6

R. Mathis*
BASF Personal Care and Nutrition GmbH
Rheinpromenade 1
40789 Monheim
Germany
E-mail: Raymond.Mathis@Cognis.com

A. Mehling
BASF Personal Care and Nutrition GmbH
Henkelstrasse 67
40551 Düsseldorf
Germany
E-mail: Annette.Mehling@Cognis.com

Chapter 7

U. S. Toti, S. G. Kumbar*, C. T. Laurencin, R. Mathew and D. Balasubramaniam
Department of Orthopaedic Surgery
Department of Chemical, Materials and Biomolecular Engineering
University of Connecticut Health Center
263 Farmington Avenue
Farmington
CT 06030
USA
E-mail: Kumbar@uchc.edu

Chapter 8

G. Song*
Department of Human Ecology
University of Alberta
Edmonton, AB
T6G 2N1
Canada
E-mail: guowen.song@ualberta.ca

W. Cao
Department of Family and Consumer Sciences
California State University – Northridge
18111 Nordhoff Street
Northridge, CA
91330-8309
USA
E-mail: wei.cao@csun.edu

R. M. Cloud
Family and Consumer Sciences
Baylor University
One Baylor Place 97346
Waco, TX
76798-7346
USA
E-mail: rinn_cloud@baylor.edu

© Woodhead Publishing Limited, 2011

Chapter 10

U. Wollina
Department of Dermatology and Allergology
Hospital Dresden-Friedrichstadt
Academic Teaching Hospital of the Technical University of Dresden
Friedrichstrasse 41
01067 Dresden
Germany
E-mail: wollina-uw@khdf.de

Chapter 11

R. Weckmann
Dr Rainer Weckmann Textile Consulting
Sulzbergring 14
74336 Brackenheim
Germany
E-mail: dr.weckmann@web.de

Chapter 12

U-C. Hipler* and C. Wiegand
Department of Dermatology and Allergology
Friedrich Schiller University Hospital Jena
Erfurter Str. 35
07740 Jena
Germany
E-mail: Christina.Hipler@med.uni-jena.de

Chapter 13

R. James
Centre for Healthcare Associated Infections
University of Nottingham
CBS Building
University Park
Nottingham
NG7 2RD
UK
E-mail: richard.james@nottingham.ac.uk

Chapter 14

F. Wiesemann* and R. Adam
Procter & Gamble Service GmbH
Sulzbacher Strasse 40
65824 Schwalbach am Taunus
Germany
E-mail: wiesemann.f@pg.com; adam.r@pg.com

Chapter 15

S. Liu
Department of Textile Sciences
University of Manitoba
Winnipeg
Manitoba R3T 2N2
Canada
E-mail: lius0@cc.umanitoba.ca

G. Sun*
Division of Textiles and Clothing
University of California, Davis
CA 95616
USA
E-mail: gysun@ucdavis.edu

Chapter 16

J. Beringer* and J. Kurz
Hohenstein Institute
Schloss Hohenstein
74357 Bönnigheim
Germany
E-mail: j.beringer@hohenstein.de; j.kurz@hohenstein.de

Chapter 17

R. H. McQueen
Department of Human Ecology
University of Alberta
Edmonton, AB
T6G 2N1
Canada
E-mail: rachel.mcqueen@ualberta.ca

© Woodhead Publishing Limited, 2011

Chapter 18

W. Zhong
Department of Textile Sciences
Faculty of Human Ecology
University of Manitoba
R3T 2N2
Canada
E-mail: zhong@cc.umanitoba.ca

Chapter 19

U. Möhring, D. Schwabe* and S. Hanus
TITV Greiz - Textilforschungsinstitut Thüringen-Vogtland e. V
Zeulenrodaerstrasse 42–44
07973 Greiz
Germany
E-mail: d.schwabe@titv-greiz.de

Chapter 20

W. Nocker
Consultant
Roseggerstrasse 9
85521 Ottobrunn
Germany
E-mail: wnocker@yahoo.de

Chapter 21

M. Walz
Eschler Textil GmbH
Max-Planck-Str. 10
72336 Balingen
Germany
E-mail: michael.walz@eschler.de

Chapter 22

C. Rotsch, H. Oschatz*, D. Schwabe, M. Weiser and U. Möhring
TITV Greiz - Textilforschungsinstitut Thüringen-Vogtland e. V
Zeulenrodaerstrasse 42–44
07973 Greiz
Germany
E-mail: h.oschatz@titv-greiz.de

Chapter 23

G. Bartkowiak* and I. Frydrych
Central Institute for Labour Protection
National Research Institute
Department of Personal Protective Equipment
Wierzbowa 48
90-133 Łódź
Poland
E-mail: grbar@ciop.lodz.pl

I. Frydrych
Technical University of Lodz
90-924 Łódź
Żwirki 36
Poland
E-mail: iwona.frydrych@p.lodz.pl

Chapter 24

L. Van der Schueren* and K. De Clerck
Department of Textiles
Ghent University
Technologiepark 907
9052 Zwijnaarde (Ghent)
Belgium
E-mail: lien.vanderschueren@ugent.be; karen.declerck@ugent.be

© Woodhead Publishing Limited, 2011

Woodhead Publishing Series in Textiles

1 **Watson's textile design and colour Seventh edition**
Edited by Z. Grosicki
2 **Watson's advanced textile design**
Edited by Z. Grosicki
3 **Weaving Second edition**
P. R. Lord and M. H. Mohamed
4 **Handbook of textile fibres Vol 1: Natural fibres**
J. Gordon Cook
5 **Handbook of textile fibres Vol 2: Man-made fibres**
J. Gordon Cook
6 **Recycling textile and plastic waste**
Edited by A. R. Horrocks
7 **New fibers Second edition**
T. Hongu and G. O. Phillips
8 **Atlas of fibre fracture and damage to textiles Second edition**
J. W. S. Hearle, B. Lomas and W. D. Cooke
9 **Ecotextile '98**
Edited by A. R. Horrocks
10 **Physical testing of textiles**
B. P. Saville
11 **Geometric symmetry in patterns and tilings**
C. E. Horne
12 **Handbook of technical textiles**
Edited by A. R. Horrocks and S. C. Anand
13 **Textiles in automotive engineering**
W. Fung and J. M. Hardcastle
14 **Handbook of textile design**
J. Wilson
15 **High-performance fibres**
Edited by J. W. S. Hearle
16 **Knitting technology Third edition**
D. J. Spencer
17 **Medical textiles**
Edited by S. C. Anand
18 **Regenerated cellulose fibres**
Edited by C. Woodings
19 **Silk, mohair, cashmere and other luxury fibres**
Edited by R. R. Franck

© Woodhead Publishing Limited, 2011

20 Smart fibres, fabrics and clothing
Edited by X. M. Tao
21 Yarn texturing technology
J. W. S. Hearle, L. Hollick and D. K. Wilson
22 Encyclopedia of textile finishing
H-K. Rouette
23 Coated and laminated textiles
W. Fung
24 Fancy yarns
R. H. Gong and R. M. Wright
25 Wool: Science and technology
Edited by W. S. Simpson and G. Crawshaw
26 Dictionary of textile finishing
H-K. Rouette
27 Environmental impact of textiles
K. Slater
28 Handbook of yarn production
P. R. Lord
29 Textile processing with enzymes
Edited by A. Cavaco-Paulo and G. Gübitz
30 The China and Hong Kong denim industry
Y. Li, L. Yao and K. W. Yeung
31 The World Trade Organization and international denim trading
Y. Li, Y. Shen, L. Yao and E. Newton
32 Chemical finishing of textiles
W. D. Schindler and P. J. Hauser
33 Clothing appearance and fit
J. Fan, W. Yu and L. Hunter
34 Handbook of fibre rope technology
H. A. McKenna, J. W. S. Hearle and N. O'Hear
35 Structure and mechanics of woven fabrics
J. Hu
36 Synthetic fibres: nylon, polyester, acrylic, polyolefin
Edited by J. E. McIntyre
37 Woollen and worsted woven fabric design
E. G. Gilligan
38 Analytical electrochemistry in textiles
P. Westbroek, G. Priniotakis and P. Kiekens
39 Bast and other plant fibres
R. R. Franck
40 Chemical testing of textiles
Edited by Q. Fan
41 Design and manufacture of textile composites
Edited by A. C. Long
42 Effect of mechanical and physical properties on fabric hand
Edited by Hassan M. Behery
43 New millennium fibers
T. Hongu, M. Takigami and G. O. Phillips

© Woodhead Publishing Limited, 2011

44 Textiles for protection
Edited by R. A. Scott
45 Textiles in sport
Edited by R. Shishoo
46 Wearable electronics and photonics
Edited by X. M. Tao
47 Biodegradable and sustainable fibres
Edited by R. S. Blackburn
48 Medical textiles and biomaterials for healthcare
Edited by S. C. Anand, M. Miraftab, S. Rajendran and J. F. Kennedy
49 Total colour management in textiles
Edited by J. Xin
50 Recycling in textiles
Edited by Y. Wang
51 Clothing biosensory engineering
Y. Li and A. S. W. Wong
52 Biomechanical engineering of textiles and clothing
Edited by Y. Li and D. X-Q. Dai
53 Digital printing of textiles
Edited by H. Ujiie
54 Intelligent textiles and clothing
Edited by H. R. Mattila
55 Innovation and technology of women's intimate apparel
W. Yu, J. Fan, S. C. Harlock and S. P. Ng
56 Thermal and moisture transport in fibrous materials
Edited by N. Pan and P. Gibson
57 Geosynthetics in civil engineering
Edited by R. W. Sarsby
58 Handbook of nonwovens
Edited by S. Russell
59 Cotton: Science and technology
Edited by S. Gordon and Y-L. Hsieh
60 Ecotextiles
Edited by M. Miraftab and A. R. Horrocks
61 Composite forming technologies
Edited by A. C. Long
62 Plasma technology for textiles
Edited by R. Shishoo
63 Smart textiles for medicine and healthcare
Edited by L. Van Langenhove
64 Sizing in clothing
Edited by S. Ashdown
65 Shape memory polymers and textiles
J. Hu
66 Environmental aspects of textile dyeing
Edited by R. Christie
67 Nanofibers and nanotechnology in textiles
Edited by P. Brown and K. Stevens

© Woodhead Publishing Limited, 2011

68 Physical properties of textile fibres Fourth edition
W. E. Morton and J. W. S. Hearle
69 Advances in apparel production
Edited by C. Fairhurst
70 Advances in fire retardant materials
Edited by A. R. Horrocks and D. Price
71 Polyesters and polyamides
Edited by B. L. Deopura, R. Alagirusamy, M. Joshi and B. S. Gupta
72 Advances in wool technology
Edited by N. A. G. Johnson and I. Russell
73 Military textiles
Edited by E. Wilusz
74 3D fibrous assemblies: Properties, applications and modelling of three-dimensional textile structures
J. Hu
75 Medical and healthcare textiles
Edited by S. C. Anand, J. F. Kennedy, M. Miraftab and S. Rajendran
76 Fabric testing
Edited by J. Hu
77 Biologically inspired textiles
Edited by A. Abbott and M. Ellison
78 Friction in textile materials
Edited by B. S. Gupta
79 Textile advances in the automotive industry
Edited by R. Shishoo
80 Structure and mechanics of textile fibre assemblies
Edited by P. Schwartz
81 Engineering textiles: Integrating the design and manufacture of textile products
Edited by Y. E. El-Mogahzy
82 Polyolefin fibres: Industrial and medical applications
Edited by S. C. O. Ugbolue
83 Smart clothes and wearable technology
Edited by J. McCann and D. Bryson
84 Identification of textile fibres
Edited by M. Houck
85 Advanced textiles for wound care
Edited by S. Rajendran
86 Fatigue failure of textile fibres
Edited by M. Miraftab
87 Advances in carpet technology
Edited by K. Goswami
88 Handbook of textile fibre structure Volume 1 and Volume 2
Edited by S. J. Eichhorn, J. W. S. Hearle, M. Jaffe and T. Kikutani
89 Advances in knitting technology
Edited by K-F. Au
90 Smart textile coatings and laminates
Edited by W. C. Smith
91 Handbook of tensile properties of textile and technical fibres
Edited by A. R. Bunsell

© Woodhead Publishing Limited, 2011

92 Interior textiles: Design and developments
Edited by T. Rowe
93 Textiles for cold weather apparel
Edited by J. T. Williams
94 Modelling and predicting textile behaviour
Edited by X. Chen
95 Textiles, polymers and composites for buildings
Edited by G. Pohl
96 Engineering apparel fabrics and garments
J. Fan and L. Hunter
97 Surface modification of textiles
Edited by Q. Wei
98 Sustainable textiles
Edited by R. S. Blackburn
99 Advances in yarn spinning technology
Edited by C. A. Lawrence
100 Handbook of medical textiles
Edited by V. T. Bartels
101 Technical textile yarns
Edited by R. Alagirusamy and A. Das
102 Applications of nonwovens in technical textiles
Edited by R. A. Chapman
103 Colour measurement: Principles, advances and industrial applications
Edited by M. L. Gulrajani
104 Textiles for civil engineering
Edited by R. Fangueiro
105 New product development in textiles: Innovation and production
Edited by L. Horne
106 Improving comfort in clothing
Edited by G. Song
107 Advances in textile biotechnology
Edited by V. A. Nierstrasz and A. Cavaco-Paulo
108 Textiles for hygiene and infection control
Edited by B. McCarthy
109 Nanofunctional textiles
Edited by Y. Li
110 Joining textiles: principles and applications
Edited by I. Jones and G. Stylios
111 Soft computing in textile engineering
Edited by A. Majumdar
112 Textile design
Edited by A. Briggs-Goode and K. Townsend
113 Biotextiles as medical implants
Edited by M. King and B. Gupta
114 Textile thermal bioengineering
Edited by Y. Li
115 Woven textile structure
B. K. Behera and P. K. Hari

© Woodhead Publishing Limited, 2011

116 Handbook of textile and industrial dyeing. Volume 1: principles processes and types of dyes
Edited by M. Clark

117 Handbook of textile and industrial dyeing. Volume 2: Applications of dyes
Edited by M. Clark

118 Handbook of natural fibres. Volume 1: Types, properties and factors affecting breeding and cultivation
Edited by R. Kozlowski

119 Handbook of natural fibres. Volume 2: Processing and applications
Edited by R. Kozlowski

120 Functional textiles for improved performance, protection and health
Edited by N. Pan and G. Sun

121 Computer technology for textiles and apparel
Edited by Jinlian Hu

122 Advances in military textiles and personal equipment
Edited by E. Sparks

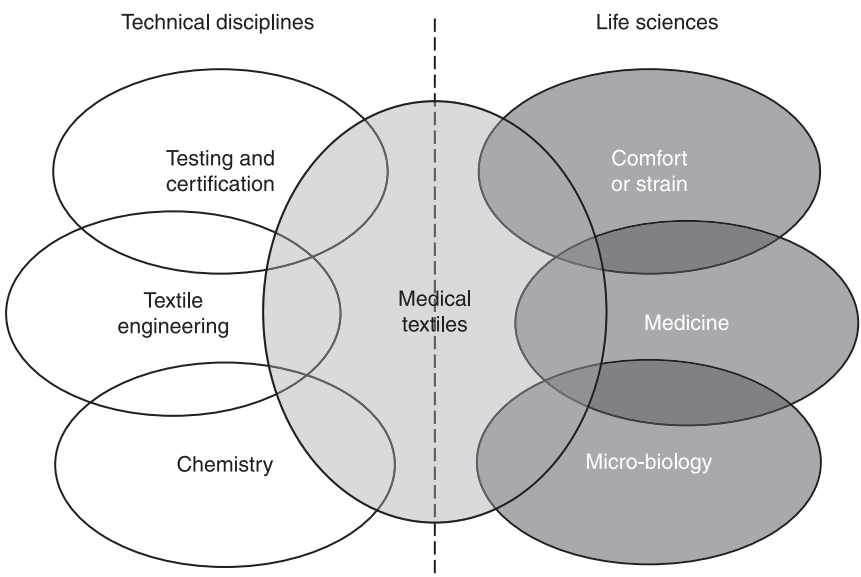
123 Specialist yarn, woven and fabric structure: Developments and applications
Edited by R. H. Gong

124 Handbook of sustainable textile production
M. Tobler

© Woodhead Publishing Limited, 2011

Preface

Some of the most thrilling applications of textiles are in their medical uses. Medical textiles are located at the interfaces between technical disciplines and life sciences (see Fig. below): On the one hand, representing the technical aspect, we find textile engineering, chemistry and testing and certification; while on the other, we have life sciences like medicine, microbiology and comfort or strain (and this is by no means a complete list). All the different sciences interact and overlap with one another. New developments in one of these sciences may boost new innovations in others, too: for example, new superabsorbent, gel-forming substances invented in chemistry led to the development of new baby diapers and adult incontinence products used in medicine. Three-dimensional spacer fabrics (textile engineering) or bio-functional clothing (chemistry) were rapidly transferred into new medical products like bandages or clothing for patients with



© Woodhead Publishing Limited, 2011

atopic eczema, respectively. Conversely, different disciplines have their own needs, which do not always coincide. For instance, coated or laminated fabrics used in ORgowns led to a significantly higher protection level against body liquids or germs (medicine, microbiology). But the wearers quickly realised that the coating or membrane has to be breathable, i.e. water-vapour permeable, otherwise the wear comfort becomes rapidly inadequate. These various connections between all different aspects make medical textiles such a challenging but fascinating field of research.

Medical textiles can be regarded as a part of the wider category of technical textiles. Here we find links with other applications as in the use of similar materials for different purposes; for example, in the operating theatre protective textiles are used which are similar to other kinds of protective clothing such as that used for chemical, bio-hazard or foul-weather protection. Keeping with this example, new developments intended for foul-weather protective clothing, like densely woven microfibre fabrics or breathable laminated textiles, were established as OR gowns, too. As a consequence the surgeon and the other operating room staff achieved a higher level of protection plus a good wear comfort.

Medical textiles are not only a fascinating research area, but are also extremely important from the economic point of view. Medical textiles are decisive elements of the progress made in medicine, which often result in new medical textile products and vice versa. Consequently medical textiles are today an inevitable constituent of modern disease management. A strong additional impetus for the need for medical textiles is generated by the increasing number of elderly people in the populations of developed countries.

Starting from common cotton fabrics, medical textiles have shown rapid development over the last few decades. This progress affects nearly all textile sectors: New, bio-degradable fibre constituents enabled novel types of implants; recent textile machines allow for three-dimensional spacer fabrics; and silver-ion based finishes effectively reduce bacteria growth. In this way the field of medical textiles has grown extensively over the years. As a consequence, it became a difficult area to understand and to review.

This book sets out to embrace several important aspects of medical textile research, development and applications. It can be taken as a starting point for readers to familiarise themselves with medical textiles, and allows experienced readers to expand their knowledge.

The book is divided into four parts: First, the types and properties of medical textiles; second, textiles and the skin; third, textiles for hygiene; and fourth, medical textile case studies and applications. The parts are further divided into several chapters. Each chapter can be regarded as a standalone review article, written by a leading expert in his field. Authors are from universities, research organisations, industry and hospitals, reflecting the diverse nature of medical textiles. Accordingly the chapters will be of great benefit to readers from a wide variety of institutions.

© Woodhead Publishing Limited, 2011

It is my privilege to edit this book. I wish to thank all authors for sharing their excellence with us and for their dedication in preparing their superb manuscripts. I would also like to thank the lovely people at Woodhead Publishing, who supported me in many cases during the evolution of this book. And last but not least it is my great pleasure to wish every reader an exciting and informative read.

Volkmar T. Bartels
Brackenheim

© Woodhead Publishing Limited, 2011

1

Modern textiles and biomaterials for healthcare

S. PETRULYTE and D. PETRULIS,
Kaunas University of Technology, Lithuania

Abstract: The chapter provides the latest information on sources and main properties of medical textiles and biomaterials. It first reviews the role of textile structures and biomaterials in healthcare then describes types and key properties of textile structures and biomaterials used for medical sector. The main features of advanced examples and innovative applications of products are given. At the end of this chapter, the future of medical textile materials is discussed.

Key words: advanced products of medical textiles, biomaterials, polymers, properties of medical textiles, textile structures.

1.1 Introduction

Because of innovative applications in today's healthcare environment, the medical textile industry and research are developing at an incredible rate, with achievements in such fields as infection control, barrier materials, wound care products and medical devices. For example, some decades ago only a few kinds of non-traditional wound dressing (as opposed to traditional ones like cotton, lint, and gauzes) were available on the healthcare product market. Nowadays, the explosion in product variety, market size and segments can be observed around the world, and virtually new products are appearing on the market. Also at the centre of current research are well known and widely used cotton and other natural fibres, such as silk, flax, and hemp. These natural fibres can be given significantly improved properties using enzymatic and other advanced biotechnological procedures as well as new methods of processing and modification of usual fibres, with the aim of overcoming their drawbacks.

Many modern medical textile products are made from polymer fibre components and their modified structures. The word 'biomaterials' is a combination of the Greek word 'bios' (everything to do with life) and 'materials' (including substances or components with certain properties which are used as input in production or manufacturing). Biomaterials can be defined simply as natural or manufactured (man-made) materials that comprise all or part of a living structure or biomedical device. So, biomaterials are essentially used and adapted for medical applications.

A biopolymer is any organic polymer. Well-known biopolymers such as starch, proteins, peptides, etc. make up much of living structures as well as the majority

© Woodhead Publishing Limited, 2011

of the biosphere. Biopolymers tend to have a well-defined structure and exhibit similar functions to natural material, and are built using a template-directed process. Biomaterials are the outcome of interdisciplinary subjects that involve the integration of natural and engineering sciences. Major applications of biomaterials include: sutures, joint replacements, artificial ligaments, tendons, wound dressings, blood vessels, heart valves, artificial skin, scaffolds enabling the tissue regeneration, protective structures, biomonitoring systems, etc.

The area of advanced medical textiles is significantly developing because of the major expansion in various fields such as implantable devices, medical devices, bandaging and pressure garments, wound healing, infection control and barrier materials, controlled release, hygiene products, the development of new intelligent textile products and textronis. The latest innovations in the field of medical textiles confirm the importance of modern techniques such as tissue engineering and nanoapplications and their great impact on advanced wound care structures.

Human beings are always in a dynamic state. Furthermore, the present day society is undergoing changes such as ageing of the population and increase in the life span of individuals, especially in Europe and the US. Various situations and hazards of human activity and civilisation also include transport accidents, effects of chemical materials, temperature, and other factors. So, these factors stimulate rapid movement of the medical and healthcare product market with the requirements for novel techniques and technologies for developing modern textile materials and polymers. Research in biomaterials and textile systems is oriented technically and technologically as well as functionally and effectively because of regular scientific inquiry into many new interdisciplinary aspects and novel developments. Virtually new products are regularly being approved following development by researchers. Using biotechnology it is possible to develop modern textile products, opening new markets and speeding up production. Besides, white biotechnologies are preventative, focussing on cleaner production processes.

1.2 The role of textile structures and biomaterials in healthcare

New generation medical textiles are an important and growing field. The importance of medical textiles is determined by their excellent physical, geometrical, and mechanical qualities, such as strength, extensibility, flexibility, air, vapour and liquid permeability, availability in two- or three-dimensional structures, variety in fibre length, fineness, cross-sectional shape, etc. Nowadays, textile products are able to combine traditional textile characteristics with modern multifunctionality and this role is constantly evolving.

Medical textiles should provide many specific functions depending on the scenario (healthcare monitoring or healing), application peculiarity, individuality

© Woodhead Publishing Limited, 2011

of the patient and so on. Specialised materials with determined functions can be included in medical textiles, extending into multifunctional systems made from natural or/and manufactured (man-made) materials.

The role of medical textiles and biomaterials is determined by their leading features, depending on the final application. Such materials could be bacteriostatic, anti-viral, non-toxic, fungistatic, highly absorbent, non-allergic, breathable, haemostatic, biocompatible and incorporating medications, and can also be designed to provide reasonable mechanical properties and comfort. A wide variety of textile structures can be used for medicine and healthcare: fibre (or filament), sliver, yarn, woven, nonwoven, knitted, crochet, braided, embroidered, composite materials, etc. Medical textiles also use materials like hydrogels, matrix (tissue engineering), films, hydrocolloids, and foams. The advantage is that the materials can be used as gels, films, sponges, foams, beads, fibres, support matrices and in blends or combinations as well. Specialised additives with special functions can be introduced in advanced products with the aim of absorbing odours, providing strong antibacterial properties, reducing pain and relieving irritation. Nanofibres are used due to their unique properties such as high surface area to volume ratio, film thinness, nanoscale fibre diameter, porosity, and light weight (Petrulyte, 2008).

1.3 Types of textiles and biomaterials for medical applications

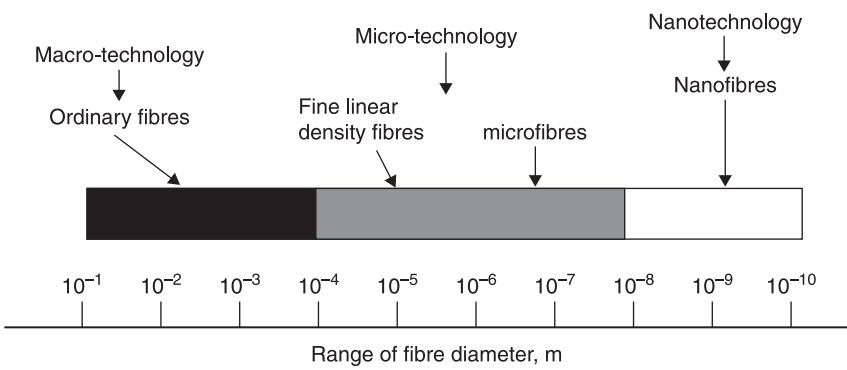
Textiles for healthcare include fibres, filaments, yarns, woven, knitted, nonwoven materials, and articles made from natural and manufactured materials as well as products utilising such raw materials. In textile products, the fibres are the main conventional structural elements. Table 1.1 shows the classification of fibres generally used for medical textiles manufacturing. The most important natural fibres for healthcare are cotton, silk and flax. These fibres are the oldest textile structures used in medical products. Meanwhile, manufactured fibres can be defined as distinct from the fibres made of natural materials. The manufactured fibres, which are applied in the healthcare sector, may be subdivided into organic and inorganic fibres. Organic fibres can be divided into two large groups based on natural and synthetic polymers. The entire spectrum of manufactured fibres from such polymers as polyester (PES), polyamide (PA), polypropylene (PP), viscose (CV) and polytetrafluoroethylene (PTFE) has found increasing application during the last decades. Polyethylene terephthalate (PET) as the most common fibre-forming PES is also used. Besides these fibres, a variety of fibrous medical materials have been derived from natural polymers, such as alginate (ALG), polylactic acid (PLA), distinct types of collagen, etc.

Manufacturing/processing technologies and fibre diameter (width for tape or film) are presented in Fig. 1.1. Textile structures used for medical products

© Woodhead Publishing Limited, 2011

Table 1.1 Classification of fibres generally used in medical textiles

Origin	Source	Examples of fibres
Natural fibres	Plant (vegetable) fibres	Bast (flax, hemp, etc.) Leaf (abaca, etc.) Seed (cotton)
	Animal fibres	Hair Silk (spider, silkworm) Wool
Manufactured (man-made) fibres	Fibres based on natural polymers	Alginates (ALG) Lyocell (CLY) Polyglycolic acid (PGA) Polylactic acid (PLA) Proteins (collagen) Viscose (CV)
	Fibres based on synthetic polymers	Elastane (EL) Elastodiene (ED) Polyamide (PA) Polyester (PES, PET) Polypropylene (PP) Polytetrafluoroethylene (PTFE) Vinylal (PVAL)
	Other fibres	Carbon (CF) Glass (GF) Metal (silver, gold, etc.) (MTF)



1.1 Manufacturing/processing technologies and fibre diameter (adapted from Sawhney *et al.*, 2008).

© Woodhead Publishing Limited, 2011

Table 1.2 Textile structures applicable for medical products, and the technique used

Structure	Technology, processes
Fibre	Natural or manufactured (man-made) fibre preparation processes
Web	Natural or manufactured (man-made) fibre preparation processes, carding
Sliver	Carding, drawing
Roving	Roving (preliminary spinning)
Spun yarn	Spinning
Filament yarn	Formation of filament (extrusion, cutting, etc.)
Plied yarn	Assembling, twisting
Fancy yarn	Spinning, twisting, knitting technique, etc.
Woven fabric	Weaving
Nonwoven material	Bonding by friction or/and cohesion or/and adhesion forces
Knitted fabric, crochet	Knitting, crochet knitting
Braided material	Braiding
Embroidered material	Embroidering
Spacer textiles	Technique enabling to hold layers by spacer
Composite material	Compositing
Modified systems	Modification using various technique as impregnation, encapsulation, printing, bonding, plasma treatment, etc.

processed using various technologies are given in Table 1.2. Each structure provides specific application possibilities:

- Vapour-permeable films, coated films, knitted gauzes and tubular bandages are known to be suitable structures for wound-care products. For example, a three-layered modern composite wound dressing is composed of a contact layer, a functional layer and a retention layer. For each layer, nonwoven material, foam material, films, yarns, and gels could be used.
- Braided tubular structures, called stents, are used as implantable intraluminal devices (Yuksekkaya and Adanur, 2009). These structures are made from polyester (PES) monofilaments.
- Materials made by electrostatic flocking technology were developed as a novel type of medical textiles (Walther *et al*., 2007). This method offers the possibility of creating matrices with anisotropic properties that have a high compressive strength despite high porosity.
- Fancy yarns, generally employed as decorative textiles, could meet the requirements for medical use: the gimp yarns with slubb effect manufactured on hollow spindle machines were developed for reinforced wound dressings (Chen *et al*., 1999).
- Ehret and Lahteenkorva (1998) suggested the following composite structure: nonwoven (manufactured from a polymer or a copolymer or a blend of polymers derived from lactic acid) and film (manufactured from a polymer of biodegradable aliphatic polyester (BAPE) type). Such composite material

© Woodhead Publishing Limited, 2011

could be applied for diapers, sanitary napkins, protective garments, surgical drapes, and surgical masks.

- A double layered woven fabric was produced from five channel PES and cotton yarns to replace regular bed sheets for patients who are at high risk of bedsores (Armakan *et al*., 2009).
- The properties of knitted medical stockings made for treatment of venous diseases must correspond to necessary functions during application concerning raw material (yarn count and composition), stocking design parameters (fineness, gradual compression, size) and wearing conditions (Radu *et al*., 2008).
- Walther *et al*. (2007) used polyamide (PA) fibres as a flock component in scaffolds for tissue engineering.
- Twisting technology has an important application in the manufacture of surgical PA threads (Zablockaite and Petrulis, 1995).
- Swiatek *et al*. (2008) developed a technology for manufacturing polyethylene terephthalate (PET) nonwoven textiles for medical applications, namely for dressing materials. In this study, melt-blowing technology and the main process parameters were proposed.
- Carbon materials prepared in the form of braids were implanted (Blazewicz, 2001).
- Lou *et al*. (2008b) investigated manufacturing and properties of polylactic acid (PLA) surgical suture. It was indicated that the PLA surgical suture composite with chitosan inhibits bacterial growth and promotes wound healing.
- Specific design criteria are significant for the development of a functional small-diameter arterial replacement graft (Isenberg *et al*., 2006). The specific values for parameters that measure target properties may depend on the nature of the artificial artery used.
- Requirements for growing tissue-engineered vascular grafts are listed by Mitchell and Niklason (2003). It is widely held that the following components are necessary: a biocompatible component with high tensile strength to provide mechanical support (collagen or analogue fibres); a biocompatible elastic component to provide recoil and prevent aneurysm formation; and a nonactivated, confluent endothelium to prevent thrombosis.
- Drug release devices based on environmentally-responsive hydrogels attract considerable attention in biomedicine with regard to relatively easy control of the release of biologically active molecules (Petrusic *et al*., 2009). The prospective study assessing the clinical performance of hydrogel dressings concludes the effectiveness for treatment of chronic wounds (Zoellner and Kapp, 2007).
- Spacer fabrics that consist of two textile layers held by spacer threads in defined and flexible spacing provide interesting textile solutions for medical use. The mechanical and micro-climate features with excellent air-permeability and thermoregulation allow use of such textile structures to prevent chronic wounds (Heide *et al*., 2005).

© Woodhead Publishing Limited, 2011

- In skin healing, mesh grafts are also used. Such grafts are made from textiles with evenly spaced holes. The neomembrane is formed in place of the implanted mesh grafts during its absorption process. Coated mesh fabric (Tavis *et al*., 1980) is used in skin substitutes for wound coverage.
- In recent years, great attention has been paid to more sophisticated multifunctional systems. Advanced technologies of hollow fibres, microfibres and other structural modifications are currently being developed (Petrulis, 2009). For instance, one of the most important applications of membrane technology is haemodialysis, where membranes are used as artificial kidneys. Rafat *et al*. (2006) investigated melt-spun polysulfone hollow fibre membranes manufactured via the thermally induced phase separation process.

The peculiarities and performance of the end textile product are affected by the qualities of previous levels of organisation.

1.4 Key properties of medical textile products

The suitability of polymeric materials and textile products applied in the healthcare field is credited to their unique origin and properties enabling them for such diverse applications as hygiene, protection, therapeutic, non-implantable or implantable materials, extracorporeal devices, etc.

Cellulose is the most widespread natural polymer, and is now the basic polymer used in the mass production of many materials for healthcare. Keratin and fibroin are structural biopolymers used for biomedical applications because of their useful properties including biodegradability and good biocompatibility. These biopolymers can be extracted from hair, wool, silk, nails, and feathers. Silk-fibroin has for centuries been used as a suitable raw material for manufacturing surgical threads. Materials obtained from natural silk-fibroin are characterised by good water vapour and air permeability, as well as high biocompatibility. Unfortunately, products such as films and sponges obtained from silk-fibroin are too fragile for biomedical applications. On the other hand, results presented by Marelli *et al*. (2008) demonstrated that mats of silk-fibroin processed by electrospinning are suitable from the morphological (fibre size and porosity), structural (stability), and biological (cytocompatibility) points of view to be applied as tissue engineering matrices for small vessel grafting.

Regenerated cellulose fibres are also used to replace traditional materials. A regenerated fibre is formed when a natural polymer or its chemical derivative is dissolved and extruded and the chemical nature of this polymer is either retained or regenerated after fibre formation. In the healthcare field, viscose (CV) fibres manufactured from cellulose are known as suitable materials. Regenerated fibres manufactured via the direct dissolution of cellulose in organic solvents are known as lyocell (CLY) fibres. CV and CLY fibres are highly hydrophilic and are not thermoplastic.

© Woodhead Publishing Limited, 2011

Alginate (ALG) as well as polyglycolic acid (PGA), polylactic acid (PLA), and their copolymers (PLGA) are biopolymers of particular interest.

Alginate (ALG) is a naturally derived polymer typically purified from seaweed. Alginates are also called polyuronides. According to Muri and Brown (2005), ALG fibres are non-toxic, non-carcinogenic, non-allergic, haemostatic, biocompatible, of reasonable strength, capable of being sterilised, amenable to manipulation to incorporate medications and easily processed. Fabia *et al*. (2005) investigated the parameters of the supermolecular structure of ALG fibres for medical applications. Le *et al*. (1997), Knill *et al*. (2004) reported that ALG and modified fibres can be used to produce yarns and fabrics for medical applications, such as drug carriers for wound healing. Conditions for manufacturing of multifunctional ALG fibres have been developed by Mikolajczyk and Wolowska-Czapnik (2005). These fibres were made from zinc alginate and copper alginate. The high moisture absorption and anti-bacterial effects of these developed fibres will allow the production of a new generation of dressing materials. The tenacity of copper alginate fibres and their modified electric properties are useful indications for materials designed for hospital linen and compression bandages.

Polyglycolic acid or polyglycolide (PGA) is known as a fibre-forming polymer, which can be polymerised directly from glycolic acid. Fibres of PGA exhibit high strength and are particularly stiff. PGA has a high melting temperature and low solubility in organic solvents. PGA is not only biodegradable; it is biocompatible, i.e. non-toxic and not usually rejected by the intended organism. It is therefore used in various biomedical applications. According to Walther *et al*. (2007), PGA is one of the most widely used scaffolding materials. PGA is also suitable for use in the field of controlled drug delivery, and is characterised by hydrolytic instability owing to the presence of the ester linkage in its backbone. Currently PGA is widely used as a material for manufacturing absorbable sutures. For instance, Absorbex® is a calcium stereate coated, synthetic absorbable braided surgical suture, made of 100% pure PGA (SSM Sterile Health Products INC, 2005). Its properties include strength, softness, minimal coefficient of friction, easy knot run-down, extremely high knot security with less number of knots and clinical safety.

Polylactic acid or polylactide (PLA) is a versatile material made from corn, sugar beet, or wheat. PLA can be polymerised directly from lactic acid. Because of the extra methyl group in the PLA repeating unit in comparison to PGA, PLA is more hydrophobic. It is an important material in the medical industry. As noted by Lou *et al*. (2008b), PLA has good biocompatibility, good biodegradability and excellent mechanical properties. This material can satisfy the need for the carrier material of cells to grow during bone tissue engineering, such as in regeneration and repair of bone and cartilage. Many scaffolds produced by textile technologies, like PLA nonwovens, are known and in principle are suitable for the proliferation of different cell types (Walther *et al*., 2007). PLA based materials are durable with a silky feel and may be blended with wool or cotton (Gokilavani and

© Woodhead Publishing Limited, 2011

Gopalakrishnan, 2009). Lou *et al*. (2008b) have reported on the manufacture and properties of PLA absorbable surgical suture.

Gokilavani and Gopalakrishnan (2009) stated that PLA and PGA are used in absorbable wound closure products, orthopaedic repair absorbable pins and fixation devices and tissue engineering structures.

As noted by Radjabian and Kish (2008), the processing conditions of poly(L-lactic acid) fibres have an effect on the structure and other properties of the fibres. It was found that the thermal and mechanical properties of filaments strongly depend on their crystalline fraction and molecular orientation. Such properties as birefringence of the filaments, thermal properties, tensile behaviour (tenacity, initial modulus, and strain at break), etc. were examined. It was concluded that filaments with different structural parameters show completely different mechanical properties.

Copolymers of PLA and PGA (PLGA) are also used for healthcare products. Materials made from PLGA have a shorter absorption time if compared with PLA. PLGA has been found to be suitable as a biodegradable polymer because it undergoes hydrolysis in the body to produce original monomers, lactic acid and glycolic acid. Also, the possibility of tailoring the polymer degradation time by altering the ratio of the monomers used during synthesis has made PLGA a common choice in the manufacturing of many healthcare products such as grafts, implants, prosthetic devices, sutures, micro and nanoparticles. Maquet *et al*. (2004) have reported that the mechanical properties of PLA and PLGA became improved by mixing with bioactive glass.

Chitin, chitosan, collagen, and gelatine are materials widely used in the production of medical textiles. Studies on the origin and qualities of these materials have been described in many papers.

Chitin is a structural polysaccharide widely found in nature. This polymer is considered the second most plentiful biomaterial, following cellulose. Potential sources for chitin production are the shells of crabs, crustaceans, shrimp and lobster; parts of insects, for example the wings of butterflies; also jellyfish, algae and fungi. Chitin is a valuable polymer with excellent bioactive properties. Chitin products are anti-bacterial, anti-viral, anti-fungal, non-toxic, and non-allergic. Chitin is insoluble in most common solvents. Three-dimensional chitin products with qualities such as soft handling, breathability, absorbency, smoothness, and non-chemical additives are ideal for dressings with wound healing properties. The method proposed by Sagar *et al*. (1991) for making a chitin-based fibrous dressing material uses a non-animal source, microfungal mycelia, as the raw material; and the resulting microfungal fibres are different from the normal spun ones. Gokilavani and Gopalakrishnan (2009) affirm the proposition that chitin is suitable for wound dressings. A method of chitin separation from the bodies of dead honeybees has been developed with the goal of preparing soluble derivatives useful in the manufacture of novel textile dressing materials (Draczynski and Szosland, 2005). Preliminary research on honeybee chitin has been carried out

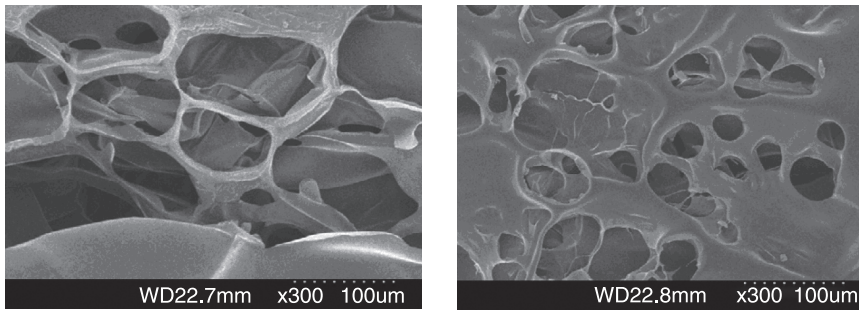
© Woodhead Publishing Limited, 2011

and soluble mixed polyesters of chitin with bioactive properties have been obtained.

Dibutyrylchitin (DBC), a soluble chitin derivative, is described as a polymer with confirmed biological properties (Chilarski *et al*., 2007). In this study, DBC was obtained in the reaction of shrimp chitin with butyric anhydride, carried out under heterogeneous condition, in which perchloric acid was used as a catalyst of reaction. In most cases, satisfactory results of wound healing were achieved.

Chitosan is a partially deacetylated form of chitin. Chitosan is biocompatible, biodegradable and can be used in gels, films, fibres, beads, support matrices and blends. Chitosan dissolves in many common aqueous acidic solutions. According to Muzzarelli *et al*. (1991), Rigby *et al*. (1997) and Ciechanska (2004), chitin/chitosan fibres and chitosan derivatives possess excellent antibacterial properties and wound healing. Bioactive composite materials with a content of antibacterial fibres and/or different functional forms of chitosan were developed (Niekraszevicz *et al*., 2007). In this study, tests were carried out in order to manufacture materials in the form of nonwovens and sponges. The antibacterial content is applied in order to suppress infection, while chitosan facilitates the healing and shortens the recovery period. Rajendran and Anand (2006), Basal *et al*. (2009), Zemljic and Persin (2009) noted that the key properties of chitin and chitosan fibres as biomedical products also include that they are haemostatic, fungistatic, and non-toxic. Examples of uses of chitosan in medical dressings, including haemostatic preparations, are also presented by Niekraszevicz (2005). Coated filaments may be applied for healthcare products; for example alginate (ALG) filaments coated in chitosan were developed for advanced wound dressings (Tamura *et al*., 2002). The chitosan coated nonwoven dressing, prepared using the immersion–precipitation phase-inversion method, had properties that could control water loss due to evaporation, promote fluid drainage and inhibit the invasion of exogenous microorganisms (Lou *et al*., 2008c). The properties of various chitosan membranes and nonwoven–chitosan membranes were investigated. The permeation of water vapour through membranes consists of two steps – adsorption and diffusion. When the concentration of chitosan solution was increased, the pore size of the membranes decreased (see Fig. 1.2). Biological features, i.e. cytotoxic and haemostatic properties of chitosan and chitosan–ALG dressing sponges were also discussed by Kucharska *et al*. (2008). As noted by Muzzarelli (1973), Khor and Lim (2003) and Basal *et al*. (2009), chitosan is used in a broad range of wound healing, drug delivery, and tissue engineering applications. Walther *et al*. (2007) tested chitosan as a substrate in the production of scaffolds for tissue engineering and polyamide (PA) flock fibres. The efficiency and biocompatibility of hormone-active fibre in the form of biologically active complex 'chitosan–insulin' *in vitro* and *in vivo* conditions were investigated (Medovic *et al*., 2008). Shin *et al*. (1999) studied antimicrobial finishing of polypropylene (PP) nonwoven fabric used as cover stock. In this research, fabrics were treated with chitosan oligomer solution. Silk–fibroin/chitosan blend films with smoothed and fibrous surfaces could play

© Woodhead Publishing Limited, 2011



(a) (b)

1.2 Morphology of chitosan membranes at different concentrations: (a) 1 wt%, (b) 2wt % (Lou *et al.,* 2008c).

an important role for carrying active antimicrobial and antioxidant compounds (Basal *et al*., 2009). This type of film made with plant extract could also find a potential application as a wound dressing contact layer material. Its valuable properties include: high surface area to volume ratio, micro-scale fibre diameter, porosity and light weight.

Collagen is the most abundant animal protein. It is the principal protein component of all connective tissues, and there are many distinct types of collagen. Each type has a specific chain composition. Collagen has been used for sutures for many years. It has controlled biodegradation rate and is biocompatible and highly pure. Collagen materials (Friess and Lee, 1996) have great potential in scaffolds for tissue culture and wound healing. Tape made from collagen I was used as substrate for fabrication of the scaffolds (Walther *et al*., 2007). The method of mineralising collagen used here was developed by Bradt *et al*. (1999). Collagen in wound dressings could appear in different physical forms, such as extruded fibres, films, and sponges. An advanced product (Still *et al*., 2003) in the generation of biological dressings is bilayered composite, a collagen sponge supporting live human allogeneic skin cells. Hybrid scaffolds for tissue repair have been produced from collagen and chitin (Lee *et al*., 2004). Gokilavani and Gopalakrishnan (2009) confirmed that collagen is used for sutures and in cell engineering structures.

Gelatine is derived from tissues such as bone, skin and cartilage and consists mainly of collagen type I and II. Gelatine melts at 37°C and starts gelling some degrees below this (Walther *et al*., 2007). It had to be used as a warm solution (temperature of 40–60°C) in order that it could be processed and act as an adhesive for flocking. As an adhesive, gelatine has been applied in scaffold manufacture (Walther *et al*. 2007). The role of artificial skin substitutes and the treatment of chronic wounds are constantly evolving (Jones *et al*., 2002). Skin substitutes are very important in burn care and are used for early burn coverage, increasing survival and leading to a better recovery of function and appearance, as well as being used for chronic wounds (Bar-Meir *et al*., 2006). Gelatine and D-glucan

© Woodhead Publishing Limited, 2011

homopolysaccharides (Lee *et al*., 2003b) have been used in the production of bioartificial skin.

Hyaluronan (also called hyaluronic acid) is a material distributed widely throughout connective, epithelial and neural tissues. Hyaluronan is able to interact with various biomolecules (Kennedy *et al*., 2001). Of course, because of solubility, rapid resorption and short tissue residence time, the direct use of hyaluronan in wound care has limitations, but hyaluronan derivatives of different solubility such as fibres, membranes, sponges and microspheres have potential. Kirker *et al*. (2002) state that hyaluronan and chondroitin sulphate can be chemically modified and made into hydrogel films with wound healing application as bio-interactive dressings. Due to its biocompatibility and its common presence in the extracellular matrix of tissues, hyaluronan is gaining popularity as a biomaterial scaffold in tissue engineering research. Walther *et al*. (2007) tested hyaluronic acid as adhesive for scaffold produced by flock technology.

Some materials could add significant functionalities to medical textiles. Silver impregnated textiles (Kim and Sun, 2000) are used as wound dressings for infected wounds, also for wounds at high risk of infection. Silver nitrate has been used as an antiseptic agent for many years. Parikh *et al*. (2005) indicated that in concentrated form, it is highly toxic to tissues. However, an aqueous solution of 0.5% silver nitrate offers significant antimicrobial activity without tissue toxicity. Silver nitrate is effective against most bacterial strains (Parikh *et al*., 2005). Silver sulfadiazine (SSD) is a superior agent used in topical treatment of burns today (Momcilovic, 2002). The antimicrobial properties of SSD were also discussed by Parikh *et al*. (2005).

Nowadays, fibres and other polymeric materials have novel functions and applications. New potential is open to fibres that could possess bio-functions as well as reasonable mechanical properties or the ability to carry medication. Both ordinary and special qualities are in demand for materials used in wound healing and management. A variety of structural, physical and mechanical properties are significant here: stable and spatial structure, purity and non-toxicity, sterility, effective barrier against microorganisms, dirt, liquid and other foreign bodies, the ability to manage exudates and fluid without causing irritation or macerating, cushioning effect, comfort, pain relieving, provision of thermal insulation, breathable, allowing gaseous exchange, mechanical protection effect, moisture and liquid absorption, easily removable without trauma, non-sensitising, non-allergic, non-harming the wound with loose fibres or other particles and healing properties that are regulated with substances added to the dressing.

1.5 Contacting behaviour and transmission phenomenon of medical-based textiles

In many applications, medical textiles contact other subjects, i.e. the substances of which the organs of the body are made. Therefore, one very important and unique

© Woodhead Publishing Limited, 2011

quality of medical textiles is biodegradability. Fibres used for healthcare are classified as biodegradable and non-biodegradable. For instance (Walther *et al*., 2007), materials used as scaffolds for tissue engineering should be biodegradable so that after new tissue has formed, no components of the scaffold are left in the body.

Biodegradable materials include cotton, viscose (CV), alginate (ALG), collagen, chitin, chitosan and others that can be absorbed by the body in two to three months. Synthetic fibres such as polyamide (PA), polyester (PES), polyethylene terephthalate (PET), polypropylene (PP) and polytetrafluoroethylene (PTFE), which take more than six months to degrade, are non-biodegradable fibres. However, this definition still has a vague meaning because of differences between researchers interpreting the terms expressing absorption, bioabsorption, and degradation processes. Absolute non-biodegradability is in some cases a principal drawback, so attempts have been made to obtain modified PP fibres (Janicki *et al*., 2009) that are at least partially biodegradable. The main advantages of these fibres are: low density, relatively good tenacity, resistance to chemical and biological agents, nearly the best heat-insulating properties and low cost of manufacturing.

Transmission features are also very important. For example, it should be noted (Podpovitny *et al*., 2008) that medical personnel appreciate two main functionalities: protection and comfort. In order to assess the suitability of different textile materials for such specific application as a dentist's gown, it is necessary to test a range of characteristics like air and water permeability, thermal resistance, cool/warm feeling etc. Light mesh knit, classically used in team sports garments, was chosen when developing prototypes for dentist gowns to improve heat transfer as well as maximum comfort of the human body.

The polymeric nature of their construction enables the products to demonstrate the concept of versatile transmission. Bearing in mind the attention turned to fluid absorption phenomenon of fibres, especially concerning modern wound dressings that provide and maintain wet conditions healing the wound effectively, the interest in highly absorbent materials remains.

According to Chen *et al*. (1999), Eaglstein (2001), Kumar *et al*. (2004), Muri and Brown (2005), Rajendran and Anand (2006) and Gokilavani and Gopalakrishnan (2009), following the moist healing concept, alginates (ALGs) which are able to absorb exudates from wound have become one of the most important materials for wound management. ALG-based products form a gel on absorption of wound exudates, thereby preventing the wound from drying out. On the contrary, traditional cotton and viscose (CV) fibres can become stuck in the wound and cause discomfort during dressing removal. Kumar *et al*. (2004) stated that soft silicone mesh is a non-adherent, porous dressing with a wound contact layer consisting of a flexible polyamide (PA) net coated with silicone. The porous nature allows fluid to pass through the secondary dressing. Vrabic *et al*. (2007) studied how plasma surface treatment modifies the absorptive characteristics of

© Woodhead Publishing Limited, 2011

CV fibres. Two different yarns, i.e. one with superior moisture wicking ability and the other one with high moisture absorption capacity were utilised in the designed woven structure (Armakan *et al*., 2009). In this study, the function of the first yarn (top layer) was to transfer moisture in vapour or liquid form quickly to the bottom layer while the function of the second yarn was to absorb moisture and keep it in the bottom layer. Russell and Mao (1999) noted that many nonwoven structures used for absorbent wound dressing exhibit anisotropic fluid transmission characteristics in-plane or in the transverse plane of the fabric structure. Such characteristics can significantly influence performance in application. Fibre orientation distribution of such materials is the main factor of major influence on anisotropic fluid transmission, and can be manipulated to design desirable transport properties. The directional permeability and the anisotropy of permeability are determined by fabric porosity and fibre diameter, orientation distribution. The phenomenon of absorption is significant for various characteristics of the textile, such as skin comfort, static build-up, water repellence, shrinkage, and wrinkle recovery.

Superabsorbent fibres (Rajedran and Anand, 2006) are made from superabsorbent polymers, which can absorb up to 50 times their own weight of water. Meanwhile, conventional wood pulp and cotton filler absorbents absorb only six times their weight. Superabsorbent fibres also present advantages such as high surface area, flexible handling and ability to form a soft product which shapes to fit the surface of the wound. Compared to powders, superabsorbent fibres absorb fluids much faster and to a very high level. Also worth noting is that the fibre, on absorbing body fluid, does not lose its fibre structure and retains its original form.

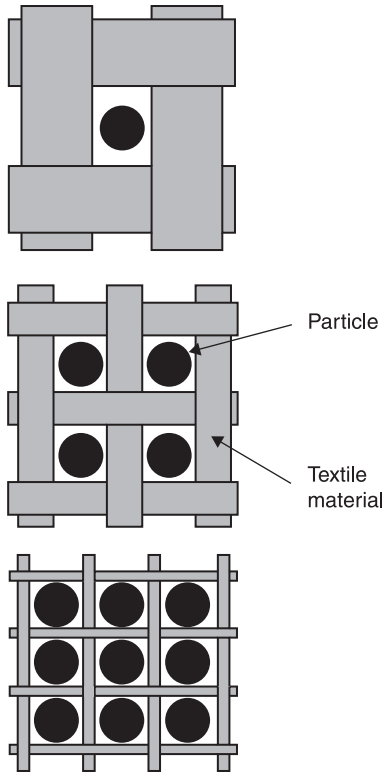
Filtration is necessary in some medical applications. In this case, liquid filtration systems may be applied. Huang *et al*. (2003) noted that filtration efficiency, which is closely associated with fibre diameter, is one of the most important concerns for filter performance (see Fig. 1.3).

One quite different kind of transmission, transmission of signals, is given below. An optical fibre is a fibre that carries light along its length. Zieba *et al*. (2007) presented optical fibre techniques in medical textile engineering. These fibres are used to transmit measured signals. For instance, the signals of breathing are necessary for a non-invasive system of health monitoring. Specially designed fibres are used for a variety of other healthcare applications, including sensors (Petrulis and Petrulyte, 2008). Most optical fibres are made from glass (GF).

1.6 Engineering stability and compactness in medical textile systems

Some kinds of perfect materials for medical purposes exhibit limitations in mechanical properties and structure. There have been many attempts to minimise or eliminate these limitations.

© Woodhead Publishing Limited, 2011



1.3 Efficiency of the filter increases with decrease in fibre diameter (adapted from Huang *et al.,* 2003).

Wilk (1999) noted that the construction of traditional textile dressings made of cotton bleached gauze is characterised by dimensional instability, flying edges, woolliness and flat surface. The new generation dressing consists of a bleached cotton fabric of leno weave structure, onto which a layer of soft paraffin material is applied. Paraffin eliminates the problem of loose fibres.

The investigators attached great importance to ALG-based materials. ALG wound dressings are made for flat wounds in the form of nonwoven material, and in the form of a sliver as well as pads for packing cavity and deep cavity wounds. As noted by Chen *et al*. (1999) and Eaglstein (2001), ALG dressings require a second dressing. In many situations, due to uptake of the wound exudates and gelling process, the fibre structure disintegrates so that the used ALG dressings can not be removed in one piece. ALG dressings reinforced with clinically acceptable non-gelling materials enable a complete and clean removal. Such a web can be generated using weaving, braiding, and knitting. Reinforced fancy gimp yarns composed of core, sheath and binder components should hold the

© Woodhead Publishing Limited, 2011

ALG fibres loosely for maximum absorbency and also provide the necessary strength to facilitate the removal of dressings. ALG fibres in twistless drawn sliver or slightly twisted roving form are used as the sheath in yarn structure with improved quality. Advanced materials for the healthcare sector were also studied by Miraftab *et al*. (1999), Rajedran and Anand (2006). Depending on the method of fabric conversion (woven, knitted, nonwoven) and also on the area of application, the branan ferulate content could be adjusted to attain the desired mechanical properties of ALG based materials (Miraftab *et al*., 1999). Steplewski *et al*. (2006) proposed different methods of manufacturing ALG–chitosan fibres. In this study, the mechanical properties as well as cross-sections of these fibres have been studied.

Chitosan nanofibres combine good functional properties such as biodegradability, biocompatibility and non-toxicity, with very bad mechanical properties. As noted by Vrieze *et al*. (2008), a layer of chitosan nanofibres was electrospun on a layer of cellulose acetate nanofibres. The resulting bilayer nonwoven has better mechanical properties than the chitosan nonwoven with the possibility of applying the material for wound dressing. Cross linked chitosan/polyethylenoxide nanofibre sheets are generally well tolerated, biocompatible and promising for use in medical and pharmaceutical applications (Lubasova and Martinova, 2008). Pure chitosan films also have poor tensile strength and elasticity. Shelma *et al*. (2008) made an attempt to develop a composite film from chitosan by incorporating chitin nanofibres to improve its mechanical properties.

Carbon materials have been investigated by Blazewicz (2001), Blazewicz *et al*. (2004). Carbon fibres that have been used in the reconstruction of soft and hard tissue injuries, have specific potential for use in the design of advanced biomaterials for various applications (Blazewicz, 2001).

Chitosan/carbon nanotube fibres, properties and structure have been studied by Krucinska *et al*. (2009). It was found that the incorporation of carbon nanotubes into the chitosan fibres at the ratio of 2% caused significant increase in their tenacity and Young's modulus.

1.7 Advanced examples of research and product development

1.7.1 Modifications from visible fibre to molecular shape

So-called 'modified products' have many advantages over traditional materials. Recent studies of medical textiles have resulted in progress in the modification of traditional materials. Tourrette *et al*. (2008) explored the idea of attaching stimuli-responsive micro-hydrogels as surface modifying systems to textile substrates. The capability of the investigated micro-hydrogels to respond to significant physiological stimuli such as temperature, humidity, and pH has been confirmed.

© Woodhead Publishing Limited, 2011

As noted by Rybicki *et al*. (2005), cotton fabric with a chitosan-modified surface absorbs antibiotic molecules from aqueous solution. The quantity of absorption depends on the degree of modification of the samples. The higher the degree of modification the higher the amount of antibiotic that can be bonded by the textile. Such cotton textile finishing enables the production of therapeutic new generation dressings for protection of surgical wounds against infections.

A relatively new and promising alternative to low hydrophilicity of synthetic fibres is the use of enzymes in surface modification; recent developments at different research groups demonstrate that enzymes are very well capable of hydrolysing synthetic materials (Nierstrasz *et al*., 2009).

Surface modification of polyamide (PA) via chitosan-based hydrogels, which are responsive to pH and temperature changes, was performed by Glampedaki *et al*. (2009). Developed stimuli-responsive PA could serve for controlled substance release and increased wear comfort with a variety of applications in protection clothing and sportswear. Matsuda *et al*. (1991) focused on modifying the collagen–glycosaminoglycan matrix through the incorporation of antibiotics.

Bacterial cellulose is a natural polymer consisting of microfibrils containing glucan chains bound together by hydrogen bonds. Ciechanska *et al*. (1998) noted that bacterial cellulose modified with chitosan combines properties such as bioactivity, biocompatibility and biodegradability of the two biopolymers creating an excellent dressing material, isolating the wound from the environment and stimulating healing. Bacterial cellulose/chitosan wound dressings (Ciehanska 2004) are innovative due to their good antibacterial and barrier properties as well as good mechanical properties and, in the wet state, high moisture retention. Such features make modified bacterial cellulose an excellent dressing material for treating various kinds of wounds, also burns and ulcers. This modified bacterial cellulose consists of microfibres with diameters in the order of tenths of a micrometre, which form a three-dimensional network. It was also estimated that chitosan has a favourable impact on the mechanical properties of modified bacterial cellulose. High elongation at break indicates good elasticity, so such dressings fit the wound site well and therefore provide good protection against external infection. Bioactive materials made from chitosan-modified bacterial cellulose provide optimal moisture conditions for rapid wound healing and stimulate wound healing without irritation or allergisation. Such composite structures have applications in the management of burns, bedsores, skin ulcers and hard-to-heal wounds as well as wounds requiring frequent dressing change (Ciechanska *et al*., 2005). In addition, the antimicrobial properties and biodegradability of modified cellulose fibres have been investigated by Tomsic and Simoncic (2009).

In recent years, high attention has been given to the bioactivity of materials. Along with biocompatibility, biosafety and high absorbency, this property is very desirable in drug delivery systems for surgical implants as well as in scaffolds for tissue regeneration. To provide fibres with bioactive properties, many researchers

© Woodhead Publishing Limited, 2011

have modified fibres. Bioactive fibres (Macken, 2003) manufactured from modified man-made fibres with an antibacterial additive introduced in the spinning process provide protection against cross-transmission of diseases and infections. The graft polymerisation of acrylic acid on polyamide 6 (PA6) fibres was examined by Buchenska (1996). In this study, the modification of PA6 fibres by adding to their structure carboxylic groups and then combining them with antibiotics was discussed.

Hormone-active fibres in the form of a fibrous artificial depot of insulin pertain to the new trend of investigations concerned with modern insulin therapy. Resorptive artificial depots of insulin were obtained by chemisorption of insulin by ALG fibres. Because of their microstructure as well as ion-exchanging ability, these fibres proved to be also convenient for chemisorption of large organic molecules such as insulin (Medovic *et al*., 2006).

A novel use for carbohydrates in textiles is the modification of textiles with cyclodextrins. As noted by Buschmann (2002), Martin Del Valle (2004) and Fleck (2006), these materials can trap body odour compounds using an inclusion complex or can be used to release perfumes or to deliver pharmaceuticals/cosmetics on skin contact. Cyclodextrins are natural cyclic oligosaccharides formed during the enzymatic degradation of starch (Grechin *et al*., 2007). Permanent fixation of cyclodextrins onto fibres is one of the attractive possibilities of chemical modification of textile materials. Wang and Chen (2005) developed aromatherapic textiles using the fragrance with beta-cyclodextrin inclusion compounds.

Thermo-sensitive hydrogels have been investigated by Petrusic *et al*. (2009). With focus on swelling-controlled drug release systems, hydrogel microbeads proved to be a promising technique for the formation of hydrogel microscale beads of regular spherical shape.

In a paper by Strobin *et al*. (2006), research on the formation of cellulose/silk–fibroin blended fibres was reported. Modification of cellulose by forming a composite with silk-fibroin might result in producing cellulose/silk-fibroin biomaterials, thus joining the properties of cellulose with those of silk-fibroin, which would be especially useful as a dressing material. In terms of application, the most interesting fibres are those with the highest silk-fibroin content and mechanical properties suitable for further processing, i.e. those with a silk-fibroin content of nine per cent.

Strobin *et al*. (2007) also discussed the results of research concerning the formation of chitosan fibres modified by silk-fibroin. In this research, silk-fibroin isolated from Bombyx mori silkworm cocoons and chitosan were used for investigations. The chitosan/silk-fibroin fibres for dressing materials were characterised by silk-fibroin content from 4.5 to 11%.

Mooney *et al*. (1996) confirm that polyglycolic acid (PGA) fibre meshes are attractive structures for cell transplantation but are incapable of resisting significant compression forces. With the aim of stabilising PGA meshes, solutions

© Woodhead Publishing Limited, 2011

of poly(L-lactic acid) (PLLA) and a 50/50 copolymer of poly(DL-lactic-*co*-glycolic acid) (PLGA) dissolved in chloroform were sprayed over meshes formed into hollow tubes. It was found that the tubes bonded with PLLA degraded more slowly than devices bonded with PLGA.

1.7.2 Modern textile architectures and specialised materials with introduced substances

Specialised materials or/and additives with special functions can be introduced in advanced medical textiles. Such special additives can absorb offensive odours from bacteria infected wounds, provide antibacterial properties (silver metals or their salts), include antiseptics, antibacterial constituents, antibiotics, zinc pastes used to sooth pain and relieve irritation, sugar pastes as deodorising agent, provide honey therapy, etc. The integration of therapeutic materials turns textiles into modern medical products. For example, advanced wound care concerns not only the materials covering the outer surface of the body, but also applies to materials like foams, hydrocolloids, hydrogels or matrix materials. Introduction of medical substances into textile structure is developed by immobilisation of medical products upon the polymer.

Gepp *et al.* (2009) presented the new method and device for encapsulating cells. It is a tool for dispensing very low volumes of ultra high viscosity medical-grade alginate (ALG) hydrogels. Contactless dispensing allows structuring of substrates with ALG, isolation and transfer of cell-alginate complexes as well as the dispensing of biological active hydrogels.

The different finishing methods and especially coatings for medical textile products represent an increasing market. Products which use coatings for medical applications include wound dressings, self-adhesive plasters, plaster bandage materials, collagen/siliconised tissues, electrically conductive materials, etc.

Silver coated fibres with an unchanged textile character are strongly required for several medical applications such as antibacterial and antistatic garments. Of course, for optimal integration into textile production, conductive fibres must allow traditional production processes like weaving, knitting and embroidering, as well as demonstrating high washing fastness. An industry-relevant plasma sputtering process was investigated to improve the mass of the deposited metal for electrical conductivity and the metal–fibre interface for adhesion (Hegemann *et al.*, 2008). Silver-plated polyester (PES) and cotton blended fabrics were determined very effective against bacteria (Jiang *et al.*, 2007). Korner *et al.* (2008) stated that coatings containing silver were applied to polyester (PES) fabrics. Further applications of such coatings can be found in the fields of textile implants and wound dressings.

Clinical trials have evaluated the efficacy and safety of a new absorbent dressing impregnated with silver salts (Lazareth *et al.*, 2007). As noted by Wang *et al.* (2007), median number of visits and treatment duration was higher; also the

© Woodhead Publishing Limited, 2011

interval between visits was shorter using silver dressing on chronic wounds versus other dressings. Therefore, these results question the effectiveness of silver dressing materials in the management of chronic wounds.

Electrically conductive textiles are increasingly demanded for medical applications, for example, they are very suitable for use as electrodes integrated in electrotherapeutic bandages that stimulate the blood flow in the human body. Schwarz *et al*. (2008) aimed to create a highly conductive, stable and skin-friendly textile. Gold is an ideal material for this purpose and can be applied in the form of a thin coating of the fabric surface. The para-aramid (AR) multifilaments were coated with a layer of gold. Chemical and electromechanical tests were performed to evaluate the actual mechanism of the formation of the gold layer, and the gold coated para-AR yarns were characterised physically and mechanically.

1.8 Future of medical textiles and products

1.8.1 Trends and challenges for new products and applications

New developments in medical textiles include their functionalisation with active (healing) components, the use of bioactive materials and the use of tissue engineering as an alternative to human donor organs (Anon., 2009a). If we are to find optimum solutions and resolve complex issues concerning the creation of comfort textiles with protection qualities, interdisciplinary work is required, including scientists from fibrous materials, textiles and clothing as well as medical staff and designers (Podpovitny *et al*., 2008). The huge innovation potential of medical textiles makes them a driving force in both industry and science. Interdisciplinary partnerships between the most diverse scientific fields enable the industry to link various functionalities in one material (Gokilavani and Gopalakrishnan, 2009).

Antibacterial, anti-UV, anti-perspiration, hypoallergenic, anti-mite, therapeutic and catalytically degrading textiles have discovered new markets in areas such as care products, controlled drug release through functionalised textiles, hygiene, disinfection and sterilisation, bedding and hypoallergenic textiles, scaffolding, noise protection/reduction, radiation and vibration. (Anon., 2009b).

Nanotechnique has acquired tremendous impulse in the last decade. Coated products like smart clothing as well as nanocoated materials are examples of current innovations. However, there is a lack of systematic information (Huang *et al*., 2003) on the relation of the mechanical properties of nanofibres to electrospinning parameters. Many challenges exist here, and a number of fundamental questions remain open.

Bioactive fibrous materials are included in functional textiles with a growing interest in medical, well-being, protection and hygienic applications (Miranda

© Woodhead Publishing Limited, 2011

et al., 2009). These products combine the performance of the textile matrix with the activity of the incorporated compound.

Biotechnology is expected to have a very large impact on animal and plant fibre production. A whole range of modern biotechnologies impacting on animal fibre production are now available including diagnostics, new vaccines and therapeutic drugs as well as technologies which modify plant fibre quality and properties (i.e. strength and length) and lead to the development of high performance textiles. New biomaterials offer special properties such as high UV resistance, controllable biodegradability, biocompatibility, improved fire resistance, super high hydrophilic property and other innovative qualities.

Bacterial colonisation remains a big problem because it is mostly followed by illness, disease and cost expansions. Therefore, the studies on infection resistant materials are very important. There is a lot of research performed in this field, but the exact mechanisms have not yet been identified. Several significant studies are given in papers by Choi *et al*. (2004); Korner *et al*. (2008) and Ilic *et al*. (2008). According to Choi *et al*. (2004), wool fibre has not been used for any biomedical applications in spite of its generic composition which is similar to other natural protein materials. In this study, the dyeing conditions of wool with antibiotics to develop novel infection resistant materials for extracorporeal biomedical and biological applications were discussed. Two antibiotics, doxycycline (Doxy) and ciprofloxacin (Cipro), were applied under a variety of temperatures, times and pH values. Korner *et al*. (2008) investigated silver-containing nanocomposite plasma coatings for textiles. Plasma technology provides an attractive, versatile tool for surface modification. These coatings can be further applied in the fields of textile implants and wound dressings. Ilic *et al*. (2008) studied the antibacterial effect of silver nanoparticles deposited on corona treated polyamide (PA) fabrics. The application of silver nanoparticles in the antibacterial finishing of textiles is favourable due to their stability and high surface to volume ratio, which provides significant bacterial efficiency.

Future concepts on the creation of new products and technologies are also discussed by Eming *et al*. (2002), Kumar *et al*. (2004), Isenberg *et al*. (2006); and Deveci and Basal (2009). Although great advances have been made in investigations of small-diameter artificial artery, many open questions remain requiring the interdisciplinary efforts of biologists, engineers, and clinicians. The enormity of the clinical need will guarantee that the investigations will continue towards the goal of producing a functional small-diameter vascular graft (Isenberg *et al*., 2006). According to Eming *et al*. (2002) and Kumar *et al*. (2004), advances in genetic technology have increased growth factor availability and their potential therapeutic role in wound healing and care. Engineered growth factors capable of proving fast and safe healing of all types of injuries including wound-related leg amputation and the like are being actively developed and improved (Eming *et al*., 2002). Microencapsulation provides several advantages for efficient stabilising, handling, storage and controlled delivery applications (Deveci and Basal, 2009).

© Woodhead Publishing Limited, 2011

1.8.2 Concepts for tissue engineering

The aim of tissue engineering is to culture viable human tissues outside the body. Introducing of biomaterials into cells and tissues to reconstruct and repair the living organisms extended the field of tissue engineering. Three-dimensional textile structures made from natural or synthetic materials are widely used as scaffolds in tissue engineering applications. Such textile scaffolds demonstrate the ability to provide necessary conditions for cell maintenance. Besides, the scaffold should have a certain shape, porosity, and volume.

Small vessels bypass grafting is now performed using mainly autografts. When no suitable autologous vessel is present, polytetrafluoroethylene (PTFE) grafts are used. Unfortunately, polymeric grafts do not have adequate properties for this application and often fail (Isenberg *et al*., 2006), so successful mimicking of the properties and biological functions of native structures is a very important goal in the fields of tissue engineering and biomaterials (Huang *et al*., 2003). Biodegradable and biocompatible polymers can be used as the matrix (Ohkawa *et al*., 2004). Culturing cells on three-dimensional biodegradable scaffolds may create tissues suitable for reconstructive surgery or as novel *in vitro* model systems (Kim *et al*., 1999).

Carbon-based implant materials were examined as scaffolds in the reconstruction of bone defects (Blazewicz, 2001). Chemically and physically functionalised carbon composites as prospective materials for tissue treatment have also been investigated (Blazewicz *et al*., 2004).

Transplanted scaffolds holding a three-dimensional cell culture should copy the characteristics of cartilage. In the regeneration of injured cartilage the scaffold material should disappear while real cartilage is healing the wound. While biodegradation is occurring the spider silk textile is overgrown with real cartilage and eventually the wound will recover without any synthetic implants (Gellynch *et al*., 2005).

Bajgai *et al*. (2008) fabricated poly(ε-caprolactone) (PCL) grafted dextran (PGD) electrospun matrix. A nanofibrous matrix with high molecular weight PGD (PGD-50) has been successfully created. The scaffold potential for tissue engineering was also investigated. The data demonstrate that a PGD-50 matrix represents a suitable substrate for supporting cell proliferation, process outgrowth and migration and as such would be a good material for an artificial extra cellular matrix. To make polycaprolactone (PCL) more suitable for tissue engineering, PLC in the form of electrospun fibrous scaffolds was first modified with 1,6-hexamethylenediamine to introduce amino groups on their structure (Mattanavee *et al*., 2009). Heart valve scaffolds (Rissanen *et al*., 2009) have been used for cardiovascular tissue engineering. Various biomolecules (collagen, chitosan) were immobilised on the surface of electrospun PLC fibrous scaffolds (Mattanavee *et al*., 2009).

Tissue engineered skin is indicated for wounds that are difficult to heal, such as diabetic foot ulcers. As noted by Naughton *et al*. (1997) and Smith (1999); in this

© Woodhead Publishing Limited, 2011

case the scaffold is a crocheted mesh manufactured from multifilament yarn on which human dermal fibroblasts are seeded and to which they attach. The result is a dermal tissue containing metabolically active cells and a dermal matrix. Tissue engineering provides viable alternatives to autograft skin which may be used in various clinical scenarios, from covering raw areas such as burns to stimulating healing in chronic wounds (Kumar *et al*., 2004). Such products could be single layered or bilayered. Due to superior biocompatibility and mechanical properties, the processing of silk-fibroin with electrospinning offers a very attractive opportunity for producing various two- and three-dimensional matrices with great potential for tissue regeneration and repair (Marelli *et al*., 2008).

The mechanical behaviour of medical fabrics currently changes upon implantation, while it is desirable to produce textiles that do not alter their mechanical properties when tissue grows in and forms a vital–avital composite. The potential of the embroidery technique was investigated for the development of textile scaffold structures for tissue engineering (Kamaruk *et al*., 1999). The results show that the embroidered textile does not undergo stiffening, whereas in the knitted fabric a rise in tensile force is observed.

Kim *et al*. (1999) investigated several biodegradable synthetic polymer scaffolds for vascular tissue engineering applications. The basic aim is to seed cells onto a degradable polymer scaffold that supports tissue growth and remodelling. Polyglycolic acid (PGA) is widely used polymer for tissue engineering; however, it is rapidly resorbed which can lead to premature weakening of the tissue before its remodelling. Kim *et al*. (1999) stated that it is necessary to improve the mechanical properties of the tissue structure and to regulate cell phenotype via interaction with the polymer.

Alginate (ALG) has certain specialised uses in textile scaffolds that may be knitted, woven, nonwoven, braided, embroidered or combined. Flexibility provides versatility and so ALG fibre systems are ideal for encouraging cells to reconstruct the tissue structure in three dimensions (Muri and Brown, 2005). Scaffold structure and porosity are key properties that will guide the formation of new tissue (Wintermantel *et al*., 1996). There is a need for structural biocompatibility of the scaffold and the host tissue. Original three-dimensional embroidered textile architecture that combines different kinds of pores, holes and stiff elements has been designed (Kamaruk *et al*., 2000). A novel type of scaffold has also been created using electrostatic flocking (Walther *et al*., 2007). This material was stable under cell culture conditions and different cell types adhered and proliferated well. Further investigations will be carried out to study the growth of cells on a blend of keratin/fibroin nanofibres in nonwovens with the aim of evaluating potential biomedical applications (Zoccola *et al*., 2008). Although the demand for arterial replacement is clear, the lower blood flow velocities of small-diameter (i.e. less than 6 mm) arteries have led to the failure of the same synthetic materials that are successful for large-diameter grafts. Researchers have explored the use of arterial tissue cells or different stem cells combined with natural and

© Woodhead Publishing Limited, 2011

synthetic scaffolds to make tubular constructs in an attempt to develop small-diameter arterial replacement grafts (Isenberg *et al*., 2006).

1.8.3 Scientific strategies in biomaterials and textiles for nanosystems and smart products

Nanosystems

Extensive research and developments in nanotechnologies and nanofibres are required in the future.

Advances in nanotechnology have created enormous opportunities and challenges for the textile industry (Sawhney *et al*., 2008). Nanofibres are very attractive due to their unique properties (Graham *et al*., 2004) such as high surface area to volume ratio, film thinness, nano scale fibre diameter, porosity of structure and lighter weight. There is high potential for nanofibres to act as drug carriers to specific sites. If drugs are to be incorporated into the nanofibre matrix, the drug must be encapsulated in the nanofibrous structure (Hussain and Ramkumar, 2006). Desirable properties of nanofibres include their mechanical behaviour and biological characteristics like biocompatibility (Huang *et al*., 2003).

Because of the small size of electrospun polymer nanofibres, the membranes collected from electrospun nanofibres possess a large surface area per unit mass and a very small pore size. These properties mean that electrospun nanofibres have many potential applications. According to Huang *et al*. (2003), one such application is medical prosthesis, mainly grafts and vessels. More extended or prospective applications which have been targeted include tissue engineering: porous membrane for skin, tubular shapes for blood vessels and nerve regenerations and three-dimensional scaffolds for bone and cartilage regeneration as well as skin healing, wound dressings, drug delivery carrier.

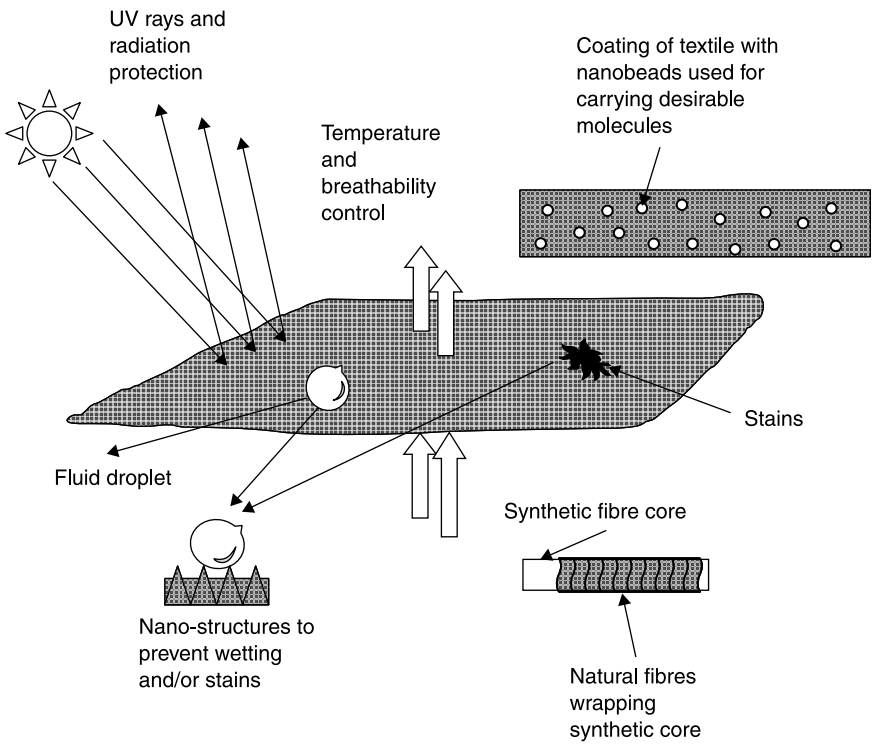
Nanostructured membranes for scaffolds could be created using electrospinning (Ohkawa *et al*., 2004). Preparation of polyethylene oxide/chitosan fibre membranes by electrospinning is discussed by Lou *et al*. (2008a). There is a lack of research available about the electrospinning of keratin but Aluigi *et al*. (2007) stated that keratin was electrospun with poly(ethylene oxide) in water, obtaining regularly shaped nanofibres. Atmospheric air and low-pressure air plasma was used for functionalisation of the raw and bleacher/mercerised cotton fabrics to achieve better adsorption of subsequently used nano-silver (Gorjanc *et al*., 2009).

There are a number of materials such as metals, metal oxides at nanoscale and biological materials such as enzymes, drugs, etc., which can add functionality to nanofibres. Such ‘value added’ nanofibres can be used effectively in protective clothing, drug delivery, tissue engineering and biomaterials, etc. Natural tissue can be weakened or lost by injury, disease, etc. Therefore, artificial supports are required in healing and repairing damaged tissues. Nanofibre scaffolds with enough mechanical and biological stability can be very important as a degradable

© Woodhead Publishing Limited, 2011

implant (Hussain and Ramkumar, 2006). Wound dressings composed of electrospun polyurethane nanofibrous membrane and silk fibroin nanofibres have also been developed. As noted by Khil *et al*. (2003) and Min *et al*. (2004), such materials are characterised by their range of pore size distribution, high surface area to volume ratio and high porosity, which are proper qualities for cell growth and proliferation. Multifilament yarn composed of chitosan and carbon nanotubes (CNT) were developed by Krucinska *et al*. (2009).

There are many ways in which the surface properties of textile can be manipulated and enhanced by implementing surface finishing, coating, and/or altering technique using nanotechnology (Sawhney *et al*., 2008). A few representative applications of textile finishing using nanotechnology are displayed in Fig. 1.4. Antibacterial disinfection and finishing techniques have been developed for many types of textiles using treatment with nanosized silver (Lee *et al*., 2003a; Wasif and Laga, 2009). Nanocrystalline silver dressings have been tested on ulcers with the result that they were completely healed after one to nine weeks of treatment. However, further studies with a larger number of patients are required (Forner-Cordero *et al*., 2007). Antimicrobial yarns (Jixiong and Jiachong, 2003) can be produced from cotton, linen,



1.4 Finishing using nanotechnology for manipulated and enhanced quality and performance of textile (adapted from Sawhney *et al.,* 2008).

© Woodhead Publishing Limited, 2011

silk, wool, polyester (PES), polyamide (PA) fibres or their blends with nanosilver particles. These yarns showed effective antimicrobial activity against various bacteria, fungi, etc. Gulrajani (2000) noted that antimicrobials containing silver have been incorporated into wound care devices as a safe and effective means of improved healing. It is known that silver in contact with a wound can enter it and become absorbed by undesirable bacteria and fungi, so silver ions kill microbes resulting in treatment of the infected wound. Ilic *et al.* (2008) highlighted the possibility of using the corona treatment for fibre surface activation, which can facilitate the efficient loading of silver nanoparticles onto PA fabrics. A stable system made from PA fabrics double loaded with silver nanoparticles demonstrated excellent antibacterial properties and satisfactory laundering durability.

Thanks to the application of nanotechnology in the fibre manufacturing process, entirely new features can be added, related to the type of nanoadditive used. By improving the mechanical stability of biodegradable nanofibrous structures and finding novel ways to incorporate functional materials functionalised nanofibres could be made into potential candidates for highly efficient biomaterials (Hussain and Ramkumar, 2006). The presence of nanoadditives in fibres determines their use for new implantable materials. Mikolajczyk *et al.* (2009) investigated conditions for the manufacture of zinc alginate fibres with a tricalcium phosphate (TCP) nanoadditive. In this study, β-TCP was used. The TCP nanoadditive was selected because of its osteoconductive activity.

The effects of ceramic nanoparticles on the rheological properties of spinning solutions of polyacrylonitrile (PAN) in dimethylformamide were examined by Mikolajczyk and Bogun (2005). In this study, the nanoparticles of silica, hydroxyapatile, and montmorillonite were used. These solutions are designed for the preparation of new-generation PAN fibres as precursor fibres to be carbonised and then used in the medical sector as materials designed for implants that could stimulate and support the process of bone reconstruction.

The advances in customer-oriented products will be the main focus for future nanotechnology applications, and the textile sector is expected to be one of the main beneficiaries. However, it goes without saying that there are some limitations and unknown health risks pertaining to the rapid development and growth of nanotechnology and nanoproducts (Sawhney *et al.*, 2008).

Smart products

In recent years, new smart products for the medical sector were also studied. The recent growth in production of medical textiles, including smart products, has renewed the interest for advanced finishing, such as antibacterial finishes as well as application of nanoparticles.

Many materials can be used in smart textiles for medicine and healthcare: biomaterials, photochromic materials, thermochromic materials, conductive polymers, fibres and yarns as well as phase change materials, light-emitting

© Woodhead Publishing Limited, 2011

polymers, optical fibres, shape memory alloys, and polymers, etc. In addition, different fabrication forms are available. For instance, the fabrication forms of shape memory alloys include films, springs, clamps, foils, and wires which can be used as components of textile structures. Shape memory polymers can be laminated onto a textile structure or compressed into a film. Phase change materials are used as microcapsules in a coating, inside fibres and in other structures.

Mazzoldi *et al*. (2002) reported on a type of smart textile able to work as a strain sensor, based on conducting polymers or carbon-filled rubbers. It can be used to create wearable devices able to read the posture and movements of a subject wearing the system, i.e. in rehabilitation. These textiles are easily integrated into truly wearable, instrumented garments, capable of recording kinaesthetic maps of human motor function with no discomfort to the wearer.

Garments that can measure a wearer's body temperature or trace their heart activity are just entering the market. Miniaturised biosensors in a textile patch can now analyse body fluids, even a tiny drop of sweat, and provide a much better assessment of the subject's health (Anon., 2008). Dermatologists have developed Derma Smart®, a T-shirt fabric that relieves itching from dry skin diseases like eczema (Anon., 2007). The fabric is made of microfibres and it is unique in that it glides over the skin's surface, it dries faster and uses small amounts of silver to prevent bacteria build-up. Smart materials could also be incorporated into the healthcare sector (Ahmed, 2009) to aid diagnostics, recording and transmitting of bio-physiological signals or ambulatory tele-monitoring of body vitals.

1.9 Sources of further information and advice

http://www.centexbel.be/Eng/research_project_biotex.htm
http://www.csiro.au/org/MedicalTextiles.html
http://www.elsevier.com/wps/find/P10_162.cws_home/main
http://www.fibre2fashion.com/industry-article/4/330/medical-textiles1.asp
http://www.fibtex.lodz.pl/49_06_13.pdf
http://www.globalsources.com/manufacturers/Medical-Textile.html
http://www.scribd.com/doc/4101166/9313
http://www.swicofil.com/biomedical_textiles.html

1.10 Acknowledgement

The authors of all published sources are gratefully acknowledged.

1.11 References

Ahmed D (2009). 'Hybridization of smart textiles in medical and healthcare management', Proceedings of AUTEX 2009 World Textile Conference, 26–28 May, Izmir. CD edition, 206–215.

© Woodhead Publishing Limited, 2011

Aluigi A, Varesano A, Montarsolo A, Vineis C, Ferrero F, Mazzuchetti G *et al.* (2007). 'Electrospinning of keratin/poly(ethylene oxide) blend nanofibers', *J Appl Polym Sci*, 104, 863–870.

Anon. Science Daily (2007). 'Clothes that relieve itch. Fabric glides over skin surface, prevents bacteria build-up'. Available: http://www.sciencedaily.com/videos/2007/0804-clothes_that_relieve_itch.htm [Accessed 18 May 2009].

Anon. Science Daily (2008). 'Smart clothes: textiles that track your health'. Available: http://www.sciencedaily.com/releases/2008/03/080329121141.htm [Accessed 18 May 2009].

Anon. CENTEXBEL (2009a). 'Medtex. Medical applications'. Available: http://www.centexbel.be/files/brochure-pdf/medtech_A4.pdf [Accessed 14 October 2009].

Anon. CENTEXBEL (2009b). 'Healthtech. Textiles for hygiene, health & wellness'. Available: http://www.centexbel.be/files/brochure-pdf/healthtech[1].pdf [Accessed 14 October 2009].

Armakan H D M, Duran D and Basal G (2009). 'Functional bed sheets for prevention of bedsores', Proceedings of AUTEX 2009 World Textile Conference, 26–28 May, Izmir. CD edition, 1487–1490.

Bajgai M P, Aryal S, Bhattarai S R, Bahadur K C R, Kim K-W and Kim H Y (2008). 'Poly(-caprolactone) grafted dextran biodegradable electrospun matrix: a novel scaffold for tissue engineering', *J Appl Polym Sci*, 108, 1447–1454.

Bar-Meir E, Mendes D and Winkler E (2006). 'Skin substitutes', *Isr Med Assoc J*, 8, 188–191.

Basal G, Altiok D, Altiok E and Bayraktar O (2009). 'Antibacterial properties of silk fibroin/chitosan blend films loaded with plant extract', Proceedings of AUTEX 2009 World Textile Conference, 26–28 May, Izmir. CD edition, 194–199.

Blazewicz M (2001). 'Carbon materials in the treatment of soft and hard tissue injuries', *Eur Cell Mater*, 2, 21–29.

Blazewicz S, Piekarczyk I, Staszkow E and Mikolajczyk T (2004). 'Chemically and physically functionalized carbon composites – a perspective material for tissue treatment', International Conference Carbon 2004, 11–16 July, Providence.

Bradt J H, Mertig M, Teresiak A and Pompe W (1999). 'Biomimetic mineralization of collagen by combined fibril assembly and calcium phosphate formation', *Chem Mater*, 11, 2694–2701.

Buchenska J (1996). 'Polyamide Fibers (PA6) with Antibacterial Properties', *J Appl Polym Sci*, 61, 567–576.

Buschmann H J (2002). 'Applications of textiles with permanently fixed cyclodextrins', International Textile, Clothing & Design Conference Magic World of Textiles, 2002, 6–9 October, Dubrovnik. University of Zagreb, Zagreb, 246–249.

Chen X, Wells G and Woods D M (1999). 'Production of yarns and fabrics from alginate fibres for medical applications', in Anand S (ed.), Proceedings of the International Conference Medical Textiles 1999, 24–25 August, Leeds. Woodhead Publishing Ltd., Cambridge, 20–29.

Chilarski A, Krucinska I, Kiekens P, Blasinska A, Schoukens G, Cislo R *et al.* (2007). 'Novel dressing materials accelerating wound healing made from dibutyrylchitin', *Fibres Text East Eur*, 15, 77–81.

Choi H-M, Bide M, Phaneuf M, Quist W and LoGerfo F (2004). 'Dyeing of wool with antibiotics to develop novel infection resistance materials for extracorporeal end use', *J Appl Polym Sci*, 92, 3343–3354.

Ciechanska D (2004). 'Multifunctional bacterial cellulose/chitosan composite materials for medical applications', *Fibres Text East Eur*, 12, 69–72.

Ciechanska D, Kazimierczak J and Gusta M (2005). 'Wound dressing materials based on chitosan modified bacterial cellulose', Proceedings of 5th International Scientific

© Woodhead Publishing Limited, 2011

Conference Medtex 2005, 28–29 November; Lodz. Printing-Office of Scientific Publications, Lodz, 44–46.
Ciechanska D, Struszczyk H and Guzinska K (1998). 'Modification of bacterial cellulose', *Fibres Text East Eur*, 6, 61–65.
Deveci S S and Basal G (2009). 'Microencapsulation by complex coacervation of chitosan and silk fibroin', Proceedings of AUTEX 2009 World Textile Conference, 26–28 May, Izmir. CD edition, 1482–1486.
Draczynski Z and Szosland L (2005). 'Honeybees and medicine', Proceedings of 5th International Scientific Conference Medtex 2005, 28–29 November, Lodz. Printing-Office of Scientific Publications, Lodz, 47–50.
Eaglstein W H (2001). 'Moist wound healing with occlusive dressings: a clinical focus', *Dermatol Surg*, 27, 175–181.
Ehret P and Lahteenkorva K (1998). 'Nonwoven/film biodegradable composite structure'. US Patent 5783504.
Eming S A, Smola H and Krieg T (2002). 'Treatment of chronic wounds: state of the art and future concepts', *Cells Tissues Organs*, 172, 105–117.
Fabia J, Slusarczyk C, Gawlowski A, Graczyk T, Wlochowicz A and Janicki J (2005). 'Supermolecular structure of alginate fibres for medical applications studied by means of WAXS and SAXS methods', *Fibres Text East Eur*, 13, 114–117.
Fleck C A (2006). 'Palliative dilemmas: wound odour' *Wound Care Canada*, 4, 10–14. Available: http://www.cawc.net/open/wcc/4-3/fleck.pdf [Accessed 2 March 2007].
Forner-Cordero I, Navarro-Monsoliu R, Munoz-Langa J, Alcober-Fuster P and Rel-Monzo P (2007). 'Use of nanocrystalline silver dressing on lymphatic ulcers in patients with chronic lymphoedema', *J Wound Care*, 16, 235–238.
Friess W and Lee G (1996). 'Basic thermo-analytical studies of insoluble collagen matrices', *Biomaterials*, 17, 2289–2294.
Gellynch K, Verdonk P, Almqvist F, Nimmen E, Bakker D D, Langenhove L *et al.* (2005). 'A spider silk supportive matrix used for cartilage regeneration' in Hongu T, Phillips G O and Takigami M (eds.), *New Millennium Fibres*, Woodhead Publishing Ltd., Cambridge, 267–268.
Gepp M M, Ehrhart F, Shirley S G, Howitz S and Zimmermann H (2009). 'Dispensing of very low volumes of ultra high viscosity alginate gels: a new tool for encapsulation of adherent cells and rapid prototyping of scaffolds and implants', *BioTechniques*, 46, 31–43.
Glampedaki P, Klein J, Warmoeskerken M M C G and Jocic D (2009). 'Surface modification of polyamide via grafted chitosan-based responsive hydrogels', Proceedings of AUTEX 2009 World Textile Conference, 26–28 May, Izmir. CD edition, 480–487.
Gokilavani R and Gopalakrishnan D (2009). 'Bio tech textiles – future trend'. Available: http://www.fibre2fashion.com/industry-article/technology-industry-article/biotech-textiles/biotech-textiles1.asp [Accessed 14 May 2009].
Gorjanc M, Jovancic P, Bukosek V and Gorensek M (2009). 'Study of adsorption of nano silver on cotton pretreated with plasma', Proceedings of AUTEX 2009 World Textile Conference, 26–28 May, Izmir. CD edition, 1029–1032.
Graham K, Schreuder-Gibson H and Gogins M (2004). 'Incorporation of electrospun nanofibers into functional structures', INJ, 13, 21–27.
Grechin A G, Buschmann H-J and Schollmeyer E (2007). 'Quantification of cyclodextrins fixed onto cellulose fibers', *Text Res J*, 77, 161–164.
Gulrajani M L (2000). 'Nano finishes', *Indian J Fibre Text Res*, 31, 187–201.

© Woodhead Publishing Limited, 2011

Hegemann D, Amberg M and Guimond S (2008). 'Plasma metallization of yarn for medical applications', Proceedings of the 8th AUTEX 2008 World Textile Conference, 24–26 June, Biela. CD edition. Available: http://www.autex2008.it/cd/ [Accessed 14 May 2009].

Heide M, Zschenderlein D and Mohring U (2005). 'Three-dimensional spacer fabrics in medicine', Proceedings of 5th International Scientific Conference Medtex 2005, 28–29 November, Lodz. Printing-Office of Scientific Publications, Lodz, 70–84.

Huang Z M, Zhang Y Z, Kotaki M and Ramakrishna S (2003). 'A review on polymer nanofibers by electrospinning and their applications in nanocomposites', *Compos Sci Technol*, 63, 2223–2253.

Hussain M M and Ramkumar S S (2006). 'Functionalized nanofibers for advanced applications', *Indian J Fibre Text Res*, 31, 41–51.

Ilic V, Saponjic Z, Vodnik V, Dimitrijevic S, Mihailovic D, *et al*. (2008). 'The antibacterial effect of silver nanoparticles deposited on corona treated polyamide fabrics', Proceedings of the 8th AUTEX 2008 World Textile Conference, 24–26 June, Biela. CD edition. Available: http://www.autex2008.it/cd/ [Accessed 5 May 2009].

Isenberg B C, Williams C and Tranquillo R T (2006). 'Small-diameter artificial arteries engineered *in vitro*', *Circ Res*, 98, 25–35.

Janicki J, Fabia J and Slusarczyk C (2009). 'Transformation of nanostructure of PP/PLA fibres under the influence of degradation process', Proceedings of AUTEX 2009 World Textile Conference, 26–28 May, Izmir. CD edition, 805–812.

Jiang S, Newton E, Yuen C-W M and Kan C-W (2007). 'Application of chemical silver plating on polyester and cotton blended fabric', *Text Res J*, 77, 85–91.

Jixiong Y and Jiachong C (2003). 'Antimicrobial yarn having nanosilver particles and methods for manufacturing the same', US Patent 0190851.

Jones I, Currie L and Martin R (2002). 'A guide to biological skin substitutes', *Br J Plast Surg*, 55, 185–193.

Kamaruk E, Mayer J, During M, Wagner B, Bischoff B, *et al*. (1999). 'Embroidery technology for medical textiles', in Anand S (ed.), Proceedings of the International Conference Medical Textiles, 1999, 24–25 August, Leeds. Woodhead Publishing Ltd., Cambridge, 200–206.

Kamaruk E, Raeber G, Mayer J, Wagner B, Bischoff B, *et al*. (2000). 'Structural and mechanical aspects of embroidered scaffolds for tissue engineering', Transactions of 6th World Biomaterials Congress, 2000, 15–20 May, Hawaii.

Kennedy J F, Knill C J and Thorley M (2001). 'Natural polymers for healing wounds', in Kennedy J F, Phillips G O, Williams P A and Hatakeyama H (eds.), *Recent Advances in Environmentally Compatible Polymers*, Woodhead Publishing Ltd, Cambridge, 97–104.

Khil M S, Cha D I, Kim H Y, Kim I S and Bhattarai N (2003). 'Electrospun nanofibrous polyurethane membrane as wound dressing', *J Biomed Mater Res B*, 67, 675–679.

Khor E and Lim L Y (2003). 'Implantable applications of chitin and chitosan', *Biomaterials*, 24, 2339–2349.

Kim B S, Nikolovski J, Bonadio J, Smiley E and Mooney D J (1999). 'Engineered smooth muscle tissues: regulating cell phenotype with the scaffold', *Exp Cell Res*, 251, 318–328.

Kim Y H and Sun G (2000). 'Dye molecules as bridges for functional modification of nylon: antimicrobial functions' *Text Res J*, 70, 728–733.

Kirker K R, Luo Y, Nielson J H, Shelby J and Prestwich G D (2002). 'Glycosaminoglycal hydrogel films as bio-interactive dressings for wound healing', *Biomaterials*, 23, 3661–3671.

© Woodhead Publishing Limited, 2011

Knill C J, Kennedy J F, Mistry J, Miraftab M, Smart G, *et al*. (2004). 'Alginate fibres modified with unhydrolysed and hydrolysed chitosans for wound dressings', *Carbohydr Polym*, 55, 65–76.

Korner E, Fortunato G, Lubben J F and Hegemann D (2008). 'Silver-containing nanocomposite plasma coatings on textiles', Proceedings of the 8th AUTEX 2008 World Textile Conference, 24–26 June, Biela. CD edition. Available: http://www.autex2008.it/cd/ [Accessed 14 May 2009].

Krucinska I, Lipp-Symonowicz B, Surma B, Steplewski W and Wawro D (2009). 'Chitosan/carbon nanotubes' fibres, their properties and structure', Proceedings of AUTEX 2009 World Textile Conference, 26–28 May, Izmir. CD edition, 216–227.

Kucharska M, Niekraszewicz A, Wisniewska-Wrona M and Brzoza-Malczewska K (2008). 'Dressing sponges made of chitosan and chitosan-alginate fibrids', *Fibres Text East Eur*, 16, 109–113.

Kumar S, Wong P F and Leaper D J (2004). 'What is new in wound healing?', *Turk J Med Sci*, 34, 147–160. Available: http://journals.tubitak.gov.tr/medical/issues/sag-04-34-3/sag-34-3-1-0403-2.pdf [Accessed 31 March 2007].

Lazareth I, Ourabah Z, Senet P, Cartier H, Sauvadet A and Bohbot S (2007). 'Evaluation of a new silver foam dressing in patients with critically colonized venous leg ulcers', *J Wound Care*, 16, 129–132.

Le Y, Anand S C and Horrocs A R (1997). 'Using alginate fibre as a drug carrier for wound healing', in Anand S C (ed.), *Medical Textiles 96*, Woodhead Publishing Ltd, Cambridge, 21–26.

Lee H J, Yeo S Y and Jeong S H (2003a). 'Antibacterial effect of nanosized silver colloidal solution on textile fabrics' *J Mater Sci*, 38, 2199–2204.

Lee S B, Jeon H W, Lee Y W, Lee Y M, Song K W, *et al*. (2003b). 'Bio-artificial skin composed of gelatin and (1 3), (1 6)–β-glucan', *Biomaterials*, 24, 2503–2511.

Lee S B, Kim Y H, Chong M S and Lee Y M (2004), 'Preparation and characteristics of hybrid scaffolds composed of β-chitin and collagen', *Biomaterials*, 25, 2309–2317.

Lou C-W, Lin J-H, Yen K-C, Lu C-T and Lee C-Y (2008a). 'Preparation of polyethylene oxide/chitosan fiber membranes by electrospinning and the evaluation of biocompatibility', *Text Res J*, 78, 254–257.

Lou C-W, Yao C-H, Chen Y-S, Hsieh T-C, Lin J-H and Hsing W-H (2008b). 'Manufacturing and properties of PLA absorbable surgical suture', *Text Res J*, 78, 958–965.

Lou C-W, Lin C-W, Chen Y-S, Yao C-H, Lin Z-S, *et al*. (2008c). 'Properties evaluation of tencel/cotton nonwoven fabric coated with chitosan for wound dressing', *Text Res J*, 78, 248–253.

Lubasova D and Martinova L (2008). 'Crosslinking chitosan/PEO nanofiber sheets friendly for medical application', Proceedings of the 8th AUTEX 2008 World Textile Conference, 24–26 June, Biela. CD edition. Available: http://www.autex2008.it/cd/ [Accessed 19 May 2009].

Macken C (2003). 'Bioactive fibres – benefits to mankind', *Chem Fibres Int*, 53, 39–41.

Maquet V, Boccaccini A R, Pravata L, Notingher I and Jerome R (2004). 'Porous poly([alpha]-hydroxyacid)/Bioglass(R) composite scaffolds for bone tissue engineering. I: preparation and *in vitro* characterization', *Biomaterials*, 25, 4185–4194.

Marelli B, Alessandrino A, Fare S, Tanzi M C and Freddi G (2008). 'Electrospun silk fibroin tubular matrices for small vessel bypass grafting', Proceedings of the 8th AUTEX 2008 World Textile Conference, 24–26 June, Biela. CD edition. Available: http://www.autex2008.it/cd/ [Accessed 9 May 2009].

© Woodhead Publishing Limited, 2011

Martin Del Valle E M (2004). 'Cyclodextrins and their uses: a review', *Process Biochem*, 9, 1033–1046.

Matsuda K, Suzuki S, Isshiki N, Yoshioka K, Okada T, *et al.* (1991). 'A bilayer artificial skin capable of sustained-release of an antibiotic', *Br J Plast Surg*, 44, 142–146.

Mattanavee W, Suwantong O, Puthong S, Bunaprasert T, Hoven V P and Supaphol P (2009). 'Immobilization of biomolecules on the surface of electrospun polycaprolactone fibrous scaffolds for tissue engineering', *ACS Appl Mater Interface*, 1, 1076–1085.

Mazzoldi A, De Rossi D, Lorussi F, Scilingo E P and Paradiso R (2002). 'Smart textiles for wearable motion capture systems', *AUTEX Res J*, 2, 19-9-203.

Medovic A, Kojic Z, Tasic G, Milakovic B, Kostic M and Skundric P (2008). 'Efficiency and biocompatibility of hormone-active polysaccharide fibers', Proceedings of the 8th AUTEX 2008 World Textile Conference, 24–26 June, Biela. CD edition. Available: http://www.autex2008.it/cd/ [Accessed 15 May 2009].

Medovic A, Skundric P, Kostic M and Djordjevic P (2006). 'Mathematical modelling of biodegradable insulin artificial depot on alginate fibers', The Book of Abstracts of ICOSECS 5 – International Conference of the Chemical Societies of the South-East European Countries, 2006, 10–14 September, Ohrid.

Mikolajczyk T and Bogun M (2005). 'Effect of ceramic nanoparticles on the rheological properties of spinning solutions of polyacrylonitrile in dimethylformamide', *Fibres Text East Eur*, 13, 28–31.

Mikolajczyk T, Bogun M, Kurzak A and Szparaga G (2009). 'Zinc alginate fibres with a tricalcium phosphate (TCP) nanoadditive', *Fibres Text East Eur*, 17, 12–18.

Mikolajczyk T and Wolowska-Czapnik D (2005). 'Multifunctional alginate fibres with anti-bacterial properties', *Fibres Text East Eur*, 13, 35–40.

Min B M, Lee G, Kim S H, Nam Y S, Lee T S and Park W H (2004). 'Electrospinning of silk fibroin nanofibers and its effect on the adhesion and spreading of normal human keratinocytes and fibroblasts in vitro', *Biomaterials*, 25, 1289–1297.

Miraftab M, Quiao Q, Kennedy J F, Anand S C and Collyer G (1999). 'Advanced materials for wound dressings: biofunctional mixed carbohydrate polymers', in Anand S (ed.), Proceedings of the International Conference Medical Textiles, 1999, 24–25 August, Leeds. Woodhead Publishing Ltd., Cambridge, 164–172.

Miranda T, Santos J and Soares G (2009). 'Bioactive textiles for well-being, medical and cosmetic applications', Proceedings of AUTEX 2009 World Textile Conference, 26–28 May, Izmir. CD edition, 200–205.

Mitchell S L and Niklason L E (2003). 'Requirements for growing tissue-engineered vascular grafts', *Cardiovasc Pathol*, 12, 59–64.

Momcilovic D (2002). 'Topical agents used in the treatment of burns', *Med Pregl* 55, 109–113.

Mooney D J, Mazzoni C L, Breuer C, McNamara K, Hern D, *et al.* (1996). 'Stabilized polyglycolic acid fibre-based tubes for tissue engineering', *Biomaterials*, 17, 115–124.

Muri J M and Brown P J (2005). 'Alginate fibres', in Blackburn R S (ed.), *Biodegradable and Sustainable Fibres*, Woodhead Publishing Ltd., Cambridge, 89–109.

Muzzarelli R A A (1973). *Natural Chelating Polymers – Alginic Acid, Chitin and Chitosan*. Pergamon Press, Oxford.

Muzzarelli R A A, Mattioli-Belmonte M, Pugnaloni A and Biagini G (1991). 'Biochemistry, histology and clinical uses of chitins and chitosans in wound healing', in Jolles P and Muzzarelli R A A (eds.), *Chitin and Chitinases*, Birkhauser Verlag, Basel, 251–264.

Naughton G, Mansbridge J and Gentzkow G (1997). 'A metabolically active human dermal

© Woodhead Publishing Limited, 2011

replacement for the treatment of diabetic foot ulcers', *Artif Organs*, 21, 1203–1210.
Niekraszewicz A (2005). 'Chitosan medical dressings', *Fibres Text East Eur*, 13, 16–18.
Niekraszewicz A, Lebioda J, Kucharska M and Wesolowska E (2007). 'Research into developing antibacterial dressing materials', *Fibres Text East Eur*, 15, 10-1-105.
Nierstrasz V A, Van Langenhove L and Kiekens P (2009). 'Biotechnological modification and functionalisation of polyester surfaces', Proceedings of AUTEX 2009 World Textile Conference, 26–28 May, Izmir. CD edition, 271–273.
Ohkawa K, Cha D I, Kim H, Nishida A and Yamamoto H (2004). 'Electrospinning of chitosan', *Macromol Rapid Commun*, 25, 1600–1605.
Parikh D V, Fink T, Rajasekharan K, Sachinvala N D, Sawhney A P S, *et al*. (2005). 'Antimicrobial silver/sodium carboxymethyl cotton dressings for burn wounds', *Text Res J*, 75, 134–138.
Petrulis D (2009). *Models of Fibres and Yarns Geometry*, Technologija, Kaunas.
Petrulis D and Petrulyte S (2008). 'Smart textiles' (in Lithuanian), *Mokslas ir Technika*, 11, 32–33, 41.
Petrulyte S (2008). 'Advanced textile materials and biopolymers in wound management', *Dan Med Bull*, 55, 72–77.
Petrusic S, Lewandowski M, Giraud S, Koncar V, Jovancic P and Bugarski B (2009). 'Thermo-sensitive hydrogels based on poly(*N*-isopropylacrylamide) for drug release system', Proceedings of AUTEX 2009 World Textile Conference, 26–28 May, Izmir. CD edition, 162–168.
Podpovitny M, Chen X, Schacher L, Adolphe D and Haikel Y (2008). 'Dentists gowns: new design for better comfort and patient's perception of professionalism', Proceedings of the 8th AUTEX 2008 World Textile Conference, 24–26 June, Biela. CD edition. Available: http://www.autex2008.it/cd/ [Accessed 5 May 2009].
Radjabian M and Kish M H (2008). 'Characterization of poly(L-lactic acid) filament yarns', Proceedings of the 8th AUTEX 2008 World Textile Conference, 24–26 June, Biela. CD edition. Available: http://www.autex2008.it/cd/ [Accessed 20 May 2009].
Radu C D, Popescu V, Manea L R, Harpa R, Piroi C, *et al*. (2008). 'Behavior of medical stockings used in chronic venous failure of leg', Proceedings of the 8th AUTEX 2008 World Textile Conference, 24–26 June, Biela. CD edition. Available: http://www.autex2008.it/cd/ [Accessed 20 May 2009].
Rafat M, Dibyendu De, Khulbe K C, Nguyen T and Matsuura T (2006). 'Surface characterization of hollow fiber membranes used in artificial kidney', *J Appl Polym Sci*, 101, 4386–4400.
Rajendran S and Anand S C (2006). 'Contribution of textiles to medical and healthcare products and developing innovative medical devices', *Indian J Fibre Text Res*, 31, 215–229.
Rigby A J, Anand S C and Horrocks A R (1997). 'Textile materials for medical and healthcare applications', *J Text Inst*, 88(Pt 3), 83–93.
Rissanen M, Puolakka A, Mariani C, Deichmann T, Schmidt D and Nousiainen P (2009). 'Composite scaffolds for cardiovascular tissue engineering made from solution spun polylactide', Proceedings of AUTEX 2009 World Textile Conference, 26–28 May, Izmir. CD edition, 188–193.
Russell S J and Mao N (1999). 'Anisotropic fluid transmission in nonwoven wound dressings', in Anand S (ed.), Proceedings of the International Conference Medical Textiles, 1999, 24–25 August, Leeds. Woodhead Publishing Ltd., Cambridge, 156–163.
Rybicki E, Filipowska B, Kozicki M, Jeziorski A and Jakubic J (2005). 'New generation

© Woodhead Publishing Limited, 2011

therapeutic dressings on the basis of surface modified textiles', Proceedings of 5th International Scientific Conference Medtex 2005, 28–29 November, Lodz. Printing-Office of Scientific Publications, Lodz, 118–121.

Sagar B, Hamlyn P and Waler D (1991). 'Wound dressing', European Patent 460774.

Sawhney A P S, Condon B, Singh K V, Pang S S, Li G and Hui D (2008). 'Modern applications of nanotechnology in textiles', *Text Res J*, 78, 731–739.

Schwarz A, Hakuzimana J, Kaczynska A, Gasana E, Banaszczyk J, *et al*. (2008). 'Characterization of gold coated yarns', Proceedings of the 8th AUTEX 2008 World Textile Conference, 24–26 June, Biela. CD edition. Available: http://www.autex2008.it/cd/ [Accessed 17 May 2009].

Shelma R, Willi Poul and Sharma C P (2008). 'Chitin nanofibre reinforced thin chitosan films for wound healing application', *Trends Biomater Artif Organs*, 22, 107–111.

Shin Y, Yoo D I andMin K (1999). 'Antimicrobial finishing of polypropylene nonwoven fabric by treatment with chitosan oligomer', *J Appl Polym Sci*, 74, 2911–2916.

Smith M (1999). 'Fibrous scaffolds for tissue culturing', in Anand S (ed.), Proceedings of the International Conference Medical Textiles, 1999, 24–25 August, Leeds. Woodhead Publishing Ltd, Cambridge, 173–179.

SSM Sterile Health Products INC (2005). Available: http://www.steril.com/eng/products-sutur-absorbex-ozelink.html [Accessed 11 May 2009].

Steplewski W, Wawro D, Niekraszewicz A and Ciechanska D (2006). 'Research into the process of manufacturing alginate–chitosan fibres', *Fibres Text East Eur*, 14, 25–31.

Still J, Glat P, Silverstein P, Griswold J and Mozingo D (2003). 'The use of a collagen sponge/living cell composite material to treat donor sites in burn patients', *Burns*, 29, 837–841.

Strobin G, Ciechanska D, Wawro D, Steplewski W, Jozwicka J, *et al*. (2007). 'Chitosan fibres modified by fibroin', *Fibres Text East Eur*, 15, 146–148.

Strobin G, Wawro D, Steplewski W, Ciehanska D, Jozwicka J, *et al*. (2006). 'Formation of cellulose/silk-fibroin blended fibres', *Fibres Text East Eur*, 14, 32–35.

Swiatek J, Jarzebowski J and Cichon J (2008). 'Investigation of fibre diameter distribution in non-woven textiles for medical applications in melt-blown polyester technology', *Fibres Text East Eur*, 16, 14–16.

Tamura H, Tsuruta Y and Tokura S (2002). 'Preparation of chitosan-coated alginate filament', *Mater Sci Eng*, 20, 143–147.

Tavis M J, Thornton J W, Bartlett R H, Roth J C and Woodroof E A (1980). 'A new composite skin prosthesis', *Burns*, 7, 123–130.

Tomsic B and Simoncic B (2009). 'Antimicrobial properties and biodegradability of cellulose modified by a cationic siloxane', Proceedings of AUTEX 2009 World Textile Conference, 26–28 May, Izmir. CD edition, 175–180.

Tourrette A, Glampedaki P, Warmoeskerken M M C G and Jocic D (2008). 'Surface modification of textile material with biopolymer-based micro- and nano-hydrogels', Proceedings of the 8th AUTEX 2008 World Textile Conference, 24–26 June, Biela. CD edition. Available: http://www.autex2008.it/cd/ [Accessed 15 May 2009].

Vrabic U, Jesih A and Svetec D G (2007). 'Physical and absorptive changes in plasma treated viscose fibres', *Fibres Text East Eur*, 15, 124–126.

Vrieze S, Van Camp T, Van Langenhove L and Kiekens P (2008). 'Electrospun chitosan and cellulose acetate as a bilayer nonwoven', Proceedings of the 8th AUTEX 2008 World Textile Conference, 24–26 June, Biela. CD edition. Available: http://www.autex2008.it/cd/ [Accessed 11 May 2009].

Walther A, Bernardt A, Pompe W, Gelinsky M, Mrozik B, *et al*. (2007). 'Development

© Woodhead Publishing Limited, 2011

of novel scaffolds for tissue engineering by flock technology', *Text Res J*, 77, 892–899.

Wang C X and Chen S L (2005). 'Aromachology and its application in the textile field', *Fibres Text East Eur*, 13, 41–44.

Wang J, Smith J, Babidge W and Maddern G (2007). 'Silver dressings versus other dressings for chronic wounds', *J Wound Care*, 16, 352–356.

Wasif A I and Laga S K (2009). 'Use of nano silver as an antimicrobial agent for cotton', *AUTEX Res J*, 9, 5–13.

Wilk E (1999). 'Some aspects of cotton leno fabric usage in the new generation of dressing materials', in Anand S (ed.), Proceedings of the International Conference Medical Textiles, 1999, 24–25 August, Leeds. Woodhead Publishing Ltd., Cambridge, 149–155.

Wintermantel E, Mayer J, Blum J, Eckert K L, Luscher P and Mathey M (1996). 'Tissue engineering scaffolds using superstructures', *Biomaterials*, 17, 83–91.

Yuksekkaya M E and Adanur S (2009). 'Analysis of polymeric braided tubular structures intended for medical applications', *Text Res J*, 79, 99–109.

Zablockaite I and Petrulis D (1995). 'Research of the structure of threads used in surgery' (in Lithuanian), *Tekstiles ir Odos Technologija*, 20, 38–45.

Zemljic L F and Persin Z (2009). 'Determination of fabric surface properties functionalized by chitosan', Proceedings of AUTEX 2009 World Textile Conference, 26–28 May, Izmir. CD edition, 1040–1043.

Zieba J, Frydrysiak M and Gniotek K (2007). 'Textronics system for breathing measurement', *Fibres Text East Eur*, 15, 105–108.

Zoccola M, Aluigi A, Piacentino M G, Vineis C, Ferrero R and Tonin C (2008). 'Keratin/fibroin blends: production and characterisation of solutions, regenerated cast films and electrospun nanofibres', Proceedings of the 8th AUTEX 2008 World Textile Conference, 24–26 June, Biela. CD edition. Available: http://www.autex2008.it/cd/ [Accessed 14 May 2009].

Zoellner P and Kapp H (2007). 'Clinical performance of a hydrogel dressing in chronic wounds: a prospective observational study', *J Wound Care*, 16, 133–136.

© Woodhead Publishing Limited, 2011

2

Hi-tech textiles for interactive wound therapies

S. RAJENDRAN and S. C. ANAND,
University of Bolton, UK

Abstract: The chapter discusses the physiology of wounds and their management. The classification of wounds and appropriate dressing selection for a successful wound management are outlined. High-tech wound dressings and the current state of the art novel dressings such as odour adsorbent and antimicrobial dressings are critically reviewed. The role of compression therapy in the treatment and prevention of venous leg ulceration is discussed. The merits and limitations of the current compression therapy regime and the research into the development of novel orthopaedic padding and compression bandages are highlighted.

Key words: wound, debridement, dressing, antibacterial, anti-odour, venous leg ulcer, padding bandage, compression bandage, spacer fabric, single-layer bandage.

2.1 Introduction

The market potential for healthcare and medical textile devices is considerably increasing. In the EU alone, sales of medical textiles are worth US$ 7 billion, and already account for 10% of the market of technical textiles. The EU sector consumes 100 000 tonnes of fibre per annum and is growing in volume by 3–4% a year. The global medical device market was valued at over US$100 billion, of which US$43 billion was generated from the US market. Western Europe is the second largest market and accounts for nearly 25% of the global medical device industry. The UK has one of the largest medical device markets in the world. The market is dominated by the National Health Service (NHS) accounting for approximately 80% of healthcare expenditure, even though there are fewer private sectors. It is forecast that the share of hygiene and medical textiles would be 12% of the global technical textiles market and would account for US$4.1 billion.

The healthcare and medical devices market is driven by:

- Population growth
- The ageing of the population
- Rising standards of living and higher expectations of quality of life
- Changing attitudes to health
- The emergence of innovations and the availability of increasingly high technology

© Woodhead Publishing Limited, 2011

It has been predicted that there is a substantial market potential for advanced wound dressings. The wound care industry generated between US$3.5 and 4.5 billion for the period from 2003 to 2006, mostly from the US and the Europe. The forecast for annual growth would be between 10% and 15% in 2012. In the US alone there are over 100 000 surgeries performed daily involving surgical wounds. An ageing population creates increased demand for all types of surgical intervention particularly cardiovascular, orthopaedic, urological and dermatological procedures. The annual cost of treating pressure ulcer accounts for 4% of the total NHS in the UK.[1] The annual cost of treating diabetic foot ulceration accounts for 5% of the total NHS in the UK.[2] The treatment of venous leg ulcer creates considerable demands upon healthcare professionals throughout the world. In the UK alone, the treatment of this condition costs the NHS £650 million per year.[3] The cost to treat an individual venous leg ulcer has been estimated to vary between £557 and £1366 over a 1-year period. In the US, venous leg ulcer affects 3.5% of people over the age of 65 and has been estimated to cost between $2.5 and $3.5 billion per year.

2.2 Wounds

A wound is a result of injury in skin and includes cuts, scratches and punctured skin. The severity of a wound depends on the damage caused in the epidermis, dermis and subcutaneous layers of the skin, and consequently, open wounds, closed wounds, burn wounds and cavity wounds are formed. Examples of open wounds are: incision wound, laceration wound, abrasion wound, bite wound, puncture wound and avulsion wound. Closed wounds are caused by a blunt impact on the skin that may rapture blood vessels and capillaries, and unlike open wounds the risk of complications are lower and are often easily treated. Burn wounds are complicated and are assessed considering the degree of depth of damage in the skin. Burn wounds are either partial thickness wounds that involve epidermal and superficial dermal layers or deep partial thickness wounds due to the injury in deep dermal layer, or full thickness wounds in which all the three layers of the skin are injured. Different terminology is used during the wound healing process such as exudating wound, sloughly wound, infected wound, black wound, green wound, pink wound, red wound and yellow wound. Exudating wounds are either moderately exudating wounds or highly exudating wounds depending on the amount of exudate secreted by the wound. A sloughly wound contains a mixture of dead tissues, inflammatory cells, dead bacteria and fibrous tissues which can be cleaned away easily. An infected wound is caused by microorganisms which resist not only the healing process but also produce offensive odour. The various stages of healing during the wound healing process are subjectively identified as black, yellow, green, red and pink wounds. A black wound is a necrotic wound and requires debridement. Sloughly wounds, infected wounds and granulating wounds are called, respectively, yellow, green and red wounds. A pink wound contains

© Woodhead Publishing Limited, 2011

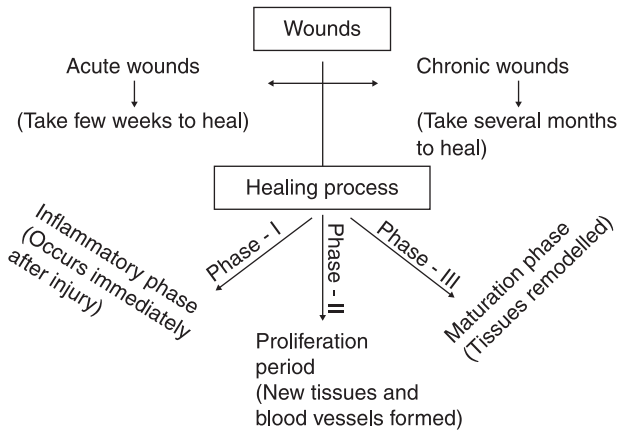
full-grown epithelial cells and is considered as the final stage of the wound healing process.

2.2.1 Wound classification

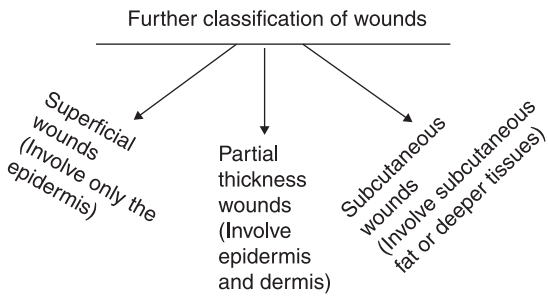
Wounds can be classified into acute wounds and chronic wounds. While acute wounds take only a few weeks to heal, chronic wounds require several months to heal completely. Chronic wounds include venous leg ulcers and pressure sores.

The classification of wounds and healing process are depicted in Fig. 2.1 and Fig. 2.2. Generally the wound healing process involves three phases:

- The inflammatory phase, which occurs immediately after injury to tissue and during which swelling takes place.
- The proliferation period, in which new tissues and blood vessels are formed.
- The maturation phase, in which tissues laid down during the proliferation stage are remodelled.



2.1 Classification of wounds and the healing process.



2.2 Classification based on the depth of wounds.

© Woodhead Publishing Limited, 2011

2.2.2 Wound management

The care and treatment of wounds is a matter of clinical judgement. The wounds should first be examined to determine the amount of exudate and whether the symptoms of infection exist. In addition, the surrounding tissue should be assessed to establish the extent of ulceration. The first stage of treatment (debridement) often requires the removal of foreign material and dead tissue from the wound in order to prevent infection and promote healing. Subsequent stages in wound management include control of exudate, stimulation of wound healing and wound protection.

Wound debridement

There are a variety of methods that can be used to debride a wound and these include autolytic, chemical, mechanical and surgical.[4] *Autolytic debridement* utilises the body's own enzymes and moisture to dissolve and clean the wound of necrotic tissue. This method has the advantage of being virtually painless for the patient but can take many weeks to achieve. A moist wound environment is the key factor to autolytic debridement and is obtained by using occlusive or semi-occlusive wound dressings.

Chemical debridement involves the use of topical enzymatic gels and solutions to dissolve and remove necrotic tissue from the wound. Different enzymes target specific components of necrotic tissue (i.e. fibrin, collagen) and are categorised as proteolytics, fibrinolytics, and collagenases.[5] This method is regarded as safe but should be limited to the area of necrosis or slough. The proteolytic enzyme fibrinolysin, which targets fibrin, is also said to release growth factors into the wound bed.[6] Fibrinolysin is normally prepared in combination with deoxyribonuclease (DNase) to form a topical ointment. A randomised study of 84 patients with chronic venous leg ulcers concluded that no long-term clinical benefit was gained by using proteolytic ointments when compared to a placebo treatment.[7]

The various methods available for *mechanical debridement* include the use of wet-to-dry dressings, whirlpool baths, and wound irrigation (pulse lavage). The wet-to-dry technique utilises saline-moistened gauze, which is applied over the wound and allowed to dry.[8] As the gauze dressing dries superficial wound debris and necrotic tissue adhere to it. Wound debridement occurs as the dressing is removed from the patient. However, this particular technique can be very painful since the dressing also adheres to living as well as necrotic tissue. Ulcer wounds may also be cleansed and debrided by using a pressurised saline solution (pulse lavage). In this technique the saline solution is passed through a catheter via a syringe in order to generate a fluid pressure of around 15 psi. The pressurised solution irrigates the wound and removes loose debris and necrotic tissue without causing pain to the patient.[8] The use of whirlpool baths has declined mainly due to the noted increase in cross-contamination and wound infection.[8]

© Woodhead Publishing Limited, 2011

The most thorough and accurate method to debride an ulcer wound is to *surgically remove* any necrotic tissue.[9] Surgical instruments (scalpel, forceps, scissors or laser) are used to cut away the dead tissue. Surgical debridement may be associated with bleeding, which can be controlled by direct pressure, electrocautery, or by cauterising the wound with silver nitrate.[8]

An emerging technique, *maggot debridement therapy* (MDT), which uses live maggots for wound debridement is now gaining popularity in managing chronic wounds. The treatment is more effective and efficient at debriding many types of infected and gangrenous wounds and ultimately enhances wound healing. The maggots are branded as the 'world's smallest surgeons' and MDT is described as 'biotherapy'. The therapy has been around for centuries but much attention is now focused for the resurgence of the treatment. The Surgical Materials Testing Laboratory (SMTL), Cardiff, UK is doing a pioneering work and is the sole UK breeder of maggots. The treatment involves the placement, using restrictive dressings, of live medical grade maggots into non-healing wounds to provide for cleansing of necrotic tissues and initiation of the healing process. Maggots clean wounds by eating dead tissues. They first spit out enzymes that liquefy the tissue and then suck it up like soup. Maggots clean wounds by dissolving the dead and infected tissues, disinfect the wound by killing bacteria and stimulate wound healing. The mechanism of maggot therapy is discussed elsewhere.[10] A study highlighted the pain level in diabetic and non-diabetic patients treated with maggot therapy.[11] An *in vivo* study conducted on 64 patients to determine the effective methods of maggot therapy revealed that containment method reduces the effectiveness of maggot debridement therapy.[12] It is reported[13] that MDT enhances the growth of granulation tissue and promotes greater wound healing rates in non-healing foot and leg ulcers. The MDT was repeatedly used for the first time on a patient in an intensive care unit (ICU) to avoid amputation of a leg.[14] There are challenges ahead for the full use of MDT at hospitals. For instance, sourcing medical grade maggots is a logistical challenge that remains a problem in many parts of the world; high cost; patients' perception and acceptability; storage and handling; training and education for tissue viability nurses; and lack of evidence-based research.

If the ulcer wound is infected with bacteria and the patient develops associated cellulitis or lymphangitis (erythema, swelling, tenderness, pain, and fever) *treatment with systemic antibiotics* is required. Various microorganisms are commonly found in wounds and wound healing can be severely impaired if a sufficient number of pathogenic species of bacteria multiply in the healthy tissue. Bacteriological examination of the ulcer wound base using swabs is required in order to determine the type of pathogens present. Culture swabs should be taken directly after wound cleansing and debriding making sure the bacteria sample is from the wound base and not from the wound edge. Information concerning the type of bacteria present allows the clinician to select an appropriate oral antibiotic therapy.

© Woodhead Publishing Limited, 2011

2.3 Wound dressings

The healing of wounds depends not only upon medication but also upon the use of proper dressing techniques and suitable dressing materials. Dressings should be easy to apply and painless on removal. They should be able to create the optimal environment for wound healing, and should be designed to reduce nursing time by requiring fewer dressing changes.

There are numerous types of wound dressings available for the management of different kinds of wounds (Table 2.1). The ideal dressing should protect the

Table 2.1 Various types of wound dressings and their applications

Type of dressing and commercial names	Major application
Low-adherent dressing Adaptic, Release, Melolin, Telfa, Skintact, Mepore, Primapore, Tricotex, NA Ultra, Jelonet, Paranet, Paratulle, Unitulle, Vasaline gauze, Inadine, Sofra-Tulle, Silicone NA, Mepitel, Metalline	Reduces risk of adherence to wounds. Less trauma
Semipermeable film dressing Mefilm, Tegaderm, Bioclusive, Cutifilm, Epi View, Opsite Flexigrid	Lightly exuding wounds, superficial pressure sores, primary dressing and secondary dressing in combination with alginates and hydrogels
Odour-adsorbing dressing Actisorb Plus, Carbonet, Kaltocarb, Metrotop, Cliniflex	For wounds that produce an undesirable odour
Hydrocolloid dressing Aquacel, Granuflex, Comfeel, Combiderm, Cutinova Foam, DuoDerm, Tegasorb, Hydrocoll	Light to medium exuding wounds. Not suitable for infected wounds
Hydrogel dressing AquaForm, Sterigel, Purilon Gel, Intrasite Gel, Granugel Hydrocolloid Gel	Dry and necrotic wounds. Lightly exuding wounds and granulating wounds. Not suitable for infected and heavily exuding wounds
Polyurethane foam dressing Allevyn, Tielle, Lyofoam, Sterigel, Nu-Gel, Purilon Gel, Intrasite Gel, Granugel, Flexipore, Spyrosorb	Light to medium exuding wounds. Not recommended for dry superficial wounds
Alginate dressing Sorbsan, Tegagel, Kaltostat, Algosteril, Algisite, Algoderm, Melgisorb, Kaltogel, Tegagel, Algosteril and Comfeelseasorb	Mainly primary dressing for medium to heavily exuding wounds and cavity wounds. Not suitable for dry wounds
Alginate–collagen dressing Fibracol	Suitable for dressing foot ulcers and heel pressure sore

© Woodhead Publishing Limited, 2011

wound, keep it moist and warm, remove exudate, promote healing, and reduce the risk of infection.[15] Primary wound dressing should have considerable capacity to absorb liquids. The absorbent dressing should be changed frequently in order to avoid wound odour and also to prevent the development of dermatitis of the surrounding skin. Switching to an occlusive dressing after the initial treatment stage provides the optimal moist environment for promoting wound healing. Occlusive dressings (i.e. hydrocolloids, hydro-gels and alginates) retain wound fluids that contain growth factors, enzymes and immune cells, which help to accelerate wound healing. In comparison to non-occlusive dry dressings, occlusive dressings also prevent bacteria from entering into the wound thereby reducing the likelihood of infection.[16] Alginate dressings exchange sodium ions with calcium ions that are exuded from the wound. The exchange in ions creates a fibrous gel, which helps to provide a moist and warm wound environment. Hydrocolloid dressings produce a similar warm and damp environment by liquefying and swelling on contact with the wound. In addition, hydrocolloid dressings provide a barrier to microorganisms and help to reduce pain by keeping surrounding nerve endings moist.[16]

2.3.1 Ideal wound dressing

Generally, the dressing is placed directly over the wound (primary dressing) and is covered with an absorbent pad (secondary dressing). The whole dressing is then retained with adhesive tape or a suitable bandage, depending on the location of the wound in the body. The primary dressing is expected to maintain the wound temperature and moisture level to permit respiration and to allow epithelial migration. The secondary dressing must not be too absorbent as it may cause the primary dressing to dry out too quickly. Different shapes are available which are suitable for dressing wounds in difficult positions such as heels, joints, digits and the perineal area.

Wound dressing materials are mainly classified as absorbent and non-absorbent, depending on the types of fibres used. Dressings vary with the type of wound and wound management and no single dressing is universally applicable.

An ideal dressing is normally expected to:

- Provide a barrier against microorganisms, dirt and other foreign bodies
- Provide a humid environment at the wound surface
- Control exudates
- Be capable of being removed without trauma.

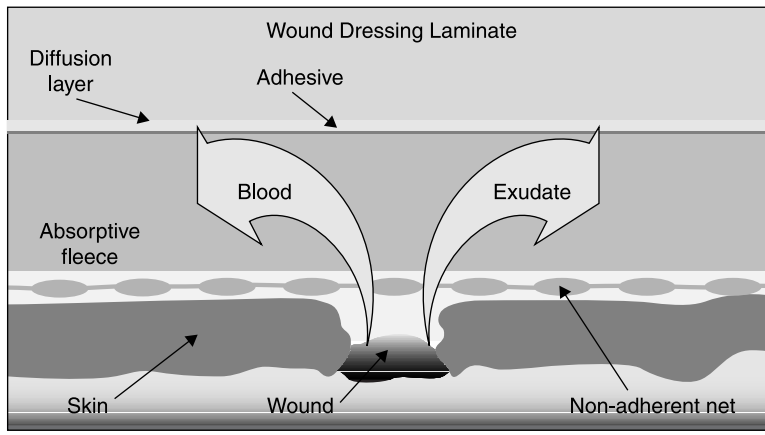
Dressings are also used to protect against further injury and abrasion by acting as a cushion and also help to promote rather than interfere with the healing process. Traditionally, cotton gauze is used for dressings because of its good absorption properties and soft handle. However, it has been established that cotton gauze allows moisture to evaporate from the wound which means that cotton

© Woodhead Publishing Limited, 2011

gauze dressings do not maintain the moist environment to facilitate faster wound healing. Furthermore, cotton gauze adheres to the wound bed. This means that patients suffer pain when the gauze is removed. Also, cotton gauze requires frequent changes. A full list of commercial wound dressings is published elsewhere.[17]

2.3.2 Wound dressing concept

A modern wound dressing consists of absorbent layers held between a wound contact layer and a base material. The absorbent layers absorb blood, body fluids and exudates. The wound contact layer is non-adherent and can easily be removed without disturbing new tissue growth. The general wound dressing model is represented in Fig. 2.3.



2.3 Wound dressing concept.

2.3.3 Hi-tech wound dressings

There are several different shapes and sizes of dressings suitable for treating wounds in difficult or awkward positions such as heels, joints, digits and the perineal area. Dressing varies with the type of wound and wound management and no single dressing is universally applicable. The ribbon gauze dressing soaked in antiseptic solution is still used for wound management because it is inexpensive. A study comparing the use of ribbon gauze soaked with antiseptic, proflavine and a hydrofibre dressing showed that the ribbon gauze was painful for the patient, extended the length of stay in hospital and necessitated more analgesia compared with the hydrofibre dressing.[18] Alginate dressing is increasingly used for the treatment of diabetic foot ulcer.[19] It forms a hard occlusive matt over the ulcer and thus prevents the continuous drainage. A novel alginate dressing (AGA-100) has

© Woodhead Publishing Limited, 2011

been developed that does not have an inhibitory effect on proliferation of fibroblasts.[20] Seven to eight rectangular 22 mm × 22 mm wounds, 0.3 mm deep, were made in the paravertebral areas of pigs and the closer rate of wounds was measured. The results showed that the closer rate of full thickness wounds treated with AGA-100 is significantly higher (98%) on day 15 compared with that of well-known Kaltostat and Sorbsan alginate dressings. A collagen–alginate wound dressing is also an effective dressing for the management of foot ulcer.[21] A calcic–sodium alginate dressing was utilised as an effective dressing in the treatment of pressure ulcers, bleeding and/or infected vascular ulcers.[22] The use of calcium alginate dressings has been shown to improve the healing of venous and decubitus ulcers by increasing granulation tissue formation.[23] It has been clinically proved that calcium/sodium alginate dressings are effective and easy to use for the treatment of cavity wounds.[24] Calcium alginate dressings reduce the severity of pain to patients with burns undergoing skin grafting and are favoured by the nursing personnel because of their ease of care.[25] It is also used as an effective haemostatic dressing to reduce post-operative pain after haemorrhoid surgery,[26] as the standard dressing for split skin donor sites[27] and as the drug delivery system for the treatment of various surgical infections.[28]

A study has shown[29] that a lyocell fibre dressing can replace the alginate dressing for the treatment of chronic wounds. Lyocell is chemically converted to produce a new fibre, Hydrocel using carboxyl methyl cellulose. The dressing is made from hydrocel gels on contact with wound fluid, like alginate, and provides a moist environment and is non-adherent. A wound dressing comprising of chitin wound facing layer and an expandable PTFE (polytetrafluoroethylene) nonwoven has been developed.[30] The chitin layer is absorbed by the body and, on the other hand, the PTFE serves as a barrier to bacteria and water. Stone *et al*.[31] studied the use of chitosan dressing for healing at skin graft donor sites. In this study half of the split skin graft donor sites were dressed with chitosan and the other half with a conventional dressing and the rate of healing evaluated. It is observed that chitosan dressing facilitated rapid wound re-epithelialisation and the regeneration of nerves within a vascular dermis. Biagini *et al*.[32] developed a chitosan derivative, *N*-carboxybutyl chitosan, dressing for treating the plastic surgery donor sites. The solution of *N*-carboxybutyl chitosan was dialysed and freeze dried to produce a soft and flexible pad, which was sterilised and applied to the wound. The dressing promoted better histoarchitectural order and better vascularisation. Muzzarelli[33] introduced a chitosan derivative, 5-methylpyrrolidinone, which has proved promising in medical applications. He claimed that this polymer is compatible with other polymer solutions including gelatin, poly(vinylalcohol), poly(vinylpyrrolidone) and hyaluronic acid. The advantages claimed by the inventor include healing of wounded meniscal tissues, healing of decubitus ulcers, depression of capsule formation around prostheses, limitation of scar formation and retraction during healing.

Mepitel is a non-adherent silicone dressing made of a medical grade silicone gel bound to a soft and pliable polyamide net.[34] It can be left in place for up to

© Woodhead Publishing Limited, 2011

two weeks and during this time the secondary dressing can be changed without risk of damaging delicate epithelial tissue. Similarly Tegapore consists of a fine polyamide net containing pores of 90 μm that permit the free passage of exudate into the secondary absorbent layer but the pores are too small to allow the ingress of granulation tissue.[35] The perforated net prevents the dressing adhering to the surface of the wound and the holes allow the passage of exudate to the absorbent layer. It may be mentioned that the ability of perforated net dressings to absorb the body fluids is limited and, therefore, a secondary absorbent dressing/pad is normally used over the primary net dressing. In this situation the absorbency of the dressing is less important than its low adherent properties. Non-adherent dressing can also be produced by coating with a thin layer of aluminium by vacuum deposition, for example Metalline.[36] It should be noted that a survey, involving nurses to study the effect of various commercial dressings such as alginates, film dressings, foam dressings, hydrocolloids, hydrogels, non-adherent dressings, paraffin tulle dressings, silicon products, knitted viscose dressings and gauze on pain, trauma and tissue damage at dressing changes showed that hydrogel dressings performed well. Seventy per cent of hydrogel dressings did not cause pain, trauma and tissue damage at dressing changes, followed by 50% of hydrofibre products and 40% of silicone products. In contrast, only 10% of non-adherent dressings did not cause pain, trauma and tissue damage at dressing changes. However, 80% of non-adherent dressings investigated rarely caused pain, trauma and tissue damage at dressing changes.[37,38]

2.3.4 Non-adherent dressings

The limitations of the currently available commercial non-adherent dressings are highlighted below:

- The majority are non-absorbent and/or hydrophobic
- A secondary absorbent dressing/pad is normally used over the primary net dressing
- The above dressings are often covered or retained in place by a tape, bandage or stocking, etc
- The majority of high absorbent dressings based on alginate, hydrogel, hydrocolloide, etc., materials do not retain their original shape or integrity once they have been used and thus wounds have to be cleaned or washed to remove the remnants of such dressings left in the wound.

The novel two-in-one high absorption and non-adherent dressings have been designed and developed to overcome the above drawbacks.[39] A number of novel knitted and crochet structures with enhanced absorbency have been designed by making use of weft knitting and crochet technologies, and this has proved that a careful examination of all possible alternatives available for the manufacture of a product could lead to the design and development of these products. A novel

© Woodhead Publishing Limited, 2011

non-adherent finish for the developed structures has also been formulated with superior properties. The salient features of the developed products for use as a primary wound dressing are listed below:

- A single layer non-adherent and high-absorption dressing
- The dressing retains its original shape and size even after use as a dressing material
- Produces gels on dressing surface that facilitate non-traumatic dressing removal
- Maintains moist environment at wound site that promotes healing
- Enhances the absorption of body fluids
- The dressing is non-toxic, non-irritant or non-allergic to humans
- High absorbent capacity and absorption rate which promote free flow of body fluids and prevent fluid pooling at the wound site thus reducing the risk of bacterial infection and wound maceration
- Gelling facilitates non-adherence to the wound which permits non-traumatic dressing removal and maintains a moist environment, which promotes wound healing, at the wound site
- New products are soft and easy to handle, viz. no gelling in the dry state. They can also be used on dry wounds, unlike alginate dressing
- A range of novel structures and finishing components has been developed and fully characterised by using commercial and relatively inexpensive medical grade fibres such as bleached cotton, bleached viscose, bleached lyocel and other natural, biodegradable and non-toxic fibres and finishing components by using conventional materials, equipment and chemicals.

2.3.5 Odour adsorption dressings

Wound malodour

Wound malodour is increasingly becoming a problem. It mostly affects patients suffering with chronic wound types. It can affect the patients in numerous social and psychological ways. Patients often find the odour too embarrassing to socialise. These patients often withdraw socially from their friends, family and loved ones which often leads to depression. The embarrassment is due to the foul odour being often misinterpreted as unhygienic and dirty. For some patients, the malodorous wound is an incurable chronic condition and is surrounded by a constant repulsive smell. Wound malodour generally affects chronic wound types such as venous leg ulcers, fungating (malignant cancerous) lesions, diabetes foot ulcers and pressure ulcers.

Causes of wound malodour

It is known that wound malodour is due to the presence of devitalised, necrotic (dead) tissue or the result of severe colonisation/infection of bacterial

© Woodhead Publishing Limited, 2011

microorganisms.[40] If the wound malodour is due to the presence of necrotic tissues, debridement can drastically reduce the malodour. If the wound malodour is due to the severe colonisation/infection, then it could be due to aerobic and anaerobic bacteria. It is now believed that anaerobic bacteria (*Bacteroides* and *Clostridium* species) are instrumental in the production of volatile odorous molecules. Often malodour is a mixture of different volatile agents such as organic acids (*n*-butyric, *n*-valeric and *n*-caproic) produced by anaerobic bacteria and amines and diamines (cadaverine and putrescine) produced during metabolic processes.[41]

Treatment methods

Methods of malodour treatment involve a combination of: (i) debridement to remove the necrotic dead tissue; (ii) a short dose of an antibiotic treatment; and (iii) a specialist odour adsorbent dressing. Currently, all the commercial odour adsorbent dressings contain a layer of highly adsorbent activated charcoal cloth. It is very efficient in the adsorption of the volatile odourous molecules.

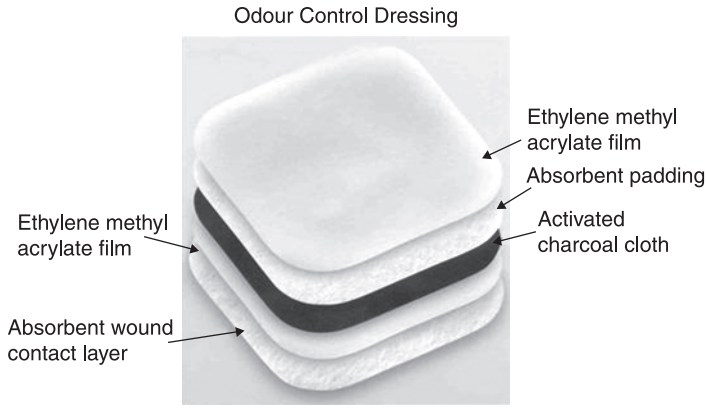
Activated charcoal cloth (ACC) wound dressings

Since 1976 the number of commercial odour adsorbent wound dressings has increased; it was not until the late 1990s that they were available on prescription in the UK. There is a wide variety of odour adsorbent wound dressings available but these can differ in construction, composition and, therefore, physical characteristics including odour adsorption. These dressings are composed of many different materials, ranging from the traditional naturally absorbent fibre types like cotton and viscose, specialist materials like polyurethane film and fibres such as alginate and carboxymethylcellulose fibres (CMC).

At present all the commercial odour adsorbent dressings contain a layer of activated charcoal cloth (ACC) (Fig. 2.4). These dressings can be loosely split into two categories, relating to their fluid up-take/absorption, either being absorbent or non-absorbent (Table 2.2). The characteristics of these specialist odour adsorbent dressings can differ from relatively simple constructions to complex multilayer composites.

The (fluid) absorbent activated charcoal wound dressings are generally composed of multilayer composites, with layers of highly adsorbent fibrous fleece or foam along with the ACC. Some of these dressings contain alginates and CMC fibres as the wound contact layer. They possess the characteristic of forming a hydrogel, therefore creating the desirable moist microenvironment which is desirable to promote wound healing. The sophistication of some of these dressings can make them relatively expensive when compared to other dressings, and this often limits them being considered during the selection for the most appropriate course of treatment.

© Woodhead Publishing Limited, 2011



2.4 Odour-absorbent dressing.

Table 2.2 Commercial odour-absorbent dressings

Dressing	Manufacturer	Main components
Carboflex	ConvaTec	ACC, absorbent multilayer with an alginate and CMC fibrous wound contact layer
Lyofoam C	Medlock	ACC, polyurethane foam
Carbonet	Smith & Nephew	ACC, absorbent multilayer laminate with a 100% viscose warp knitted wound contact layer with claimed low adhesion
Sorbsan plus carbon	Pharma-plast Ltd	ACC absorbent multilayer laminate with an alginate fibrous wound contact layer
Actisorb silver 220	Johnson & Johnson	ACC with silver, nonwoven polyamide
Carbopad VC	Vernon Carus	ACC, nonwoven polyamide
Clinisorb	CliniMed Ltd	ACC, nonwoven polyamide laminate
(Std) Melolin	Smith & Nephew	Absorbent cotton and polyester fibrous fleece with a perforated polyester film contact layer

ACC, activated charcoal cloth; CMC, carboxymethylcellulose.

The odour adsorbent ACC is sandwiched/encapsulated between two layers of a polyamide nonwoven fabric. A popular example is Actisorb silver 220 (formally known as Actisorb plus) by Johnson & Johnson which is the first to incorporate a layer of ACC to make an odour adsorbent dressing. Also, this is, currently, the only odour adsorbent dressing that possesses antimicrobial properties. The

© Woodhead Publishing Limited, 2011

antibacterial silver is incorporated into the ACC layer. The ACC with the silver has to be in close contact with the wound's surface in order for the silver ions to react with the bacteria causing the infection. Therefore, there is a risk of ACC prematurely becoming saturated with the wound fluids which can highly compromise the odour adsorption efficiency. Currently, a range of naturally occurring polymers is being investigated at the University of Bolton as alternative odour adsorbent materials to activated charcoal dressings. It should be mentioned that ACC dressings are not indicated for dry wounds.

2.3.6 Antimicrobial wound dressings

Bioactive fibres and polymers are high molecular weight natural and synthetic macromolecules and their complexes. The biomaterial research is focused in wound healing and antimicrobial materials where the design and mechanism of the biologically active molecule plays a key role in the textile fibre function. By achieving more insight into the actual activity of the molecule on the textile surface, it is possible to develop novel wound healing and antimicrobial materials. Mechanism of fibre activity is directly related to the complex biological environment surrounding the fibre. Hence, this interdisciplinary subject area has brought together physical science disciplines from textile synthetic, analytical and polymer chemistry with life science disciplines of medicine, biochemistry, biophysics and microbiology.

Scientists have been working on the issues that underpin making more efficient wound dressings and antiseptic textiles for more than a century. The molecular bases of disease processes are better understood now, and our basic understanding of the structure and function of biologically active molecules does enable the creation of bioactive fibres that can selectively interact with their biological environment. Some scientists have coined the term 'smart fabrics' to depict the targeted function these types of textiles have and their ability to perform a specific function in wound healing, arterial implants, or antimicrobial activity.

Many types of wound dressings have been developed, both non-medicated and medicated. Commercially available synthetic wound dressings consisting of a polyurethane membrane are capable of minimising evaporative water loss from the wound and preventing bacterial invasion and thus are useful in the management of superficial second-degree burns. The ideal structure of an illuminate dressing consists of an outer membrane and an inner three-dimensional matrix of fabric or sponge. The outer membrane prevents body fluid loss, controls water evaporation and protects the wound from bacterial invasion. On the other hand, the inner matrix encourages wound adherence by tissue growth into the matrix. Silver/nanosilver is mostly incorporated in the wound dressing which provides an antimicrobial shield against a wide range of bacteria. The antibacterial effect of silver was already known in ancient times. Silver tools and containers were used in around 4000 BC for storing and transporting water, to prevent the formation of

© Woodhead Publishing Limited, 2011

germs and ensure high water quality. A number of wound dressings containing silver have recently been developed. Thomas[42] critically discussed the role of silver in wound dressing. These dressing function by the sustained release of low concentrations of silver ions over time, and generally appear to stimulate healing as well as inhibiting microorganisms. The evaluation of silver-impregnated dressings, as with other topical therapies, includes *in vitro* antibacterial studies, animal models and clinical testing.

It has been argued that antimicrobial efficacy alone is insufficient benefit in modern wound dressings, and that additional properties promoting wound healing are required. Based on this, the ability to remove any undesirable bacterial products in the wound environment that impinge on healing would be a bonus, for example binding bacterial endotoxin (toxins released on cell death) to a silver dressing would be of benefit. Materials incorporated into modern silver-based dressings such as hydrocolloids, charcoal and polymers are included as an aid to wound management, but also modulate the release of silver ion. Silver exhibits a selective toxicity in bacterial cells and yeasts through its action on cell membranes, respiratory enzymes and DNA. Silver-impregnated polyamide cloths are effective antibiotics and are designed to deliver silver ions to wound sites without potential side effects, the silver is rendered harmless as it is lost naturally as the wound heals. The systemic toxicity of silver is not well documented, but silver sulfadiazine used in the treatment of burn wounds is implicated as a cause of leucopenia and renal damage. In addition to silver, natural products such as honey, aloe vera and neem are potential antibacterial agents for modern wound dressing. A systematic review of the use of honey in wound dressing has been published elsewhere.[43]

2.4 Venous leg ulcers and their treatment

2.4.1 Venous leg ulcers

About one per cent of the adult population suffers from venous leg ulcers in the UK.[44] The condition mainly affects the elderly, especially women, and is a result of a previous venous thrombosis or incompetent venous valve within the superficial or communicating veins.[45] Approximately 400 000 patients have initial symptom of leg ulcer and 100 000 have open leg ulcers that require treatment.[46] The prevalence of leg ulcers increases with age affecting 1.69% of patients aged between 65 and 95 years. The incidence rate for patients in this age group is estimated at 0.76% for men and 1.42% for women.[47] Venous ulcers are the most common type of leg ulceration. Approximately 80% of patients who have leg ulceration suffer with a venous ulcer. Arterial disease, which may coexist with venous disease, accounts for a further 10% to 25% of all leg ulcer cases. Chronic leg ulcers are defined as those lasting six weeks or more.[48] Some patients may have more than one episode of venous ulceration with estimated recurrence rates ranging from 6% to 15%.[49]

© Woodhead Publishing Limited, 2011

Venous ulcers appear in the gaiter area of the lower limb between the ankle and mid-calf. They can vary in size ranging from very small to large ulcers that extend beyond the gaiter area. The wound is characteristically shallow, irregular in shape, and has sloping well-defined borders. Typically, the skin surrounding the wound is thickened and hyper-pigmented indicating lipodermatosclerosis.[50] With chronic ulcers a yellow–white exudate is observed signifying the presence of slough. A shiny appearance indicates a fibrinous base, which inhibits new tissue formation and wound healing. Varicose veins and ankle oedema often accompany a venous ulcer.[51] Approximately 80% of patients who have a venous leg ulcer suffer from some form of discomfort, while 20% experience severe or unremitting pain.[52]

2.4.2 Causes of venous leg ulcers

It is important that the arterial and venous systems should work properly without causing problems to blood circulation around the body. Pure blood flows from the heart to the legs through arteries taking oxygen and food to the muscles, skin and other tissues. Blood then flows back to the heart carrying away waste products through veins. The valves in the veins are unidirectional which means that they allow the venous blood to flow in upward direction only. If the valves do not work properly or there is not enough pressure in the veins to push back the venous blood towards the heart, the pooling of blood in the veins takes place and this leads to higher pressure to the skin. Because of high pressure and lack of availability of oxygen and food, the skin deteriorates and eventually the ulcer occurs. The initial indications of venous leg ulcers are the swollen veins (varicose veins) and blood clots in veins (deep vein thrombosis, DVT), a growing problem for passengers on long-haul flights.

2.4.3 Diagnosis of venous leg ulcers

The diagnosis of lower limb ulceration must start by determining the patient's full clinical history together with a physical examination of the condition. It is essential to identify possible risk factors that could cause ulceration or impact on the treatment of the ulcer. These risk factors could include arterial insufficiency, trauma, diabetes, sickle cell disease, infection, malignancy or inflammatory disorders.[53]

Several non-invasive test methods are available to the clinician for investigating the cause of leg ulceration and venous insufficiency. These test methods help to assess the arterial and venous circulation of the patient and can provide information on the location of blood reflux or an obstruction within the veins.

Doppler ultrasonography

Doppler ultrasonography is used to measure the Ankle Brachial Pressure Index (ABPI) of the patient. The ultrasound technique produces a signal that identifies

© Woodhead Publishing Limited, 2011

the presence of blood flow within the arteries. The ABPI is obtained by measuring the systolic blood pressure within the dorsalis pedis or posterior tibial artery of the lower limb and the ipsilateral brachial artery of the arm.[54] The ratio between the ankle systolic pressure and the brachial systolic pressure provides the ABPI value. Measurement of the ABPI is important in order to exclude arterial disease as the cause of ulceration or as a possible risk factor that might inhibit treatment. An ABPI of >0.9 is normal, whereas patients with moderate to severe arterial disease have an ABPI that is between 0.5 and 0.8.[53] These patients should be excluded from high-compression bandage therapy since its use could lead to further ulcer complications or even limb amputation.[55] The Doppler measurement technique produces elevated readings when diagnosing patients that may have diabetes and other conditions with calcified arteries.[56]

Ultrasound scanning

Colour duplex ultrasound scanning is currently the technique of choice in order to assess the venous system of the lower limb. The technique combines ultrasound imaging with pulsated Doppler ultrasound and provides detailed anatomic information of the superficial, deep, and perforating venous systems. It can identify specific veins in which blood reflux occurs or obstructions which may be contributing to venous hypertension.[57]

Photoplethysmography and air plethysmography

Photoplethysmography and air plethysmography are simple tests designed to evaluate calf muscle dysfunction and degree of venous reflux. The techniques are used to observe the change in blood volume within the lower limb before and after exercise. Application of a tourniquet to restrict blood flow within the superficial system allows the deep venous system to be assessed for a potential obstruction.

Invasive venous tests such as ascending and descending phlebography are also used to assess venous insufficiency. Phlebography combines electromagnetic radiation (X-rays) and fluorescent materials to provide a technique that allows the veins to be clearly visualised. These immuno-fluorescence methods can detect venous outflow obstructions, provide information of valvular incompetence, and also highlight the presence of pericapillary fibrin.[58] Phlebography is usually used before a patient undergoes valvular surgery.

2.4.4 Compression therapy

It should be stated that venous leg ulcers are chronic and there is no medication or surgery to cure the disease other than the compression therapy. A sustained graduated compression mainly enhances the flow of blood back to the heart, improves the functioning of valves and calf muscle pumps, reduces oedema and

© Woodhead Publishing Limited, 2011

prevents the swelling of veins. Mostly elderly people are prone to developing DVT, varicose veins and venous leg ulcers. Venous leg ulcers are the most frequently occurring type of chronic wound accounting for 80–90% of all lower extremity ulceration.

It has been established that compression therapy, by making use of compression bandages, is an efficient treatment for healing various leg ulcers, despite surgical strategies, electromagnetic therapy and intermittent pneumatic compression. Venous leg ulcers are the most common type of ulcers and their prevalence increases with age. They are chronic and are caused due to poor venous return from the calf to the heart.

Classification of compression bandages

Compression bandages are mainly classified as elastic and non-elastic. Elastic compression bandages (Table 2.3) are categorised according to the level of pressure generated on the angle of an average leg. Class 3a bandages provide light compression of 14–17 mmHg, moderate compression (18–24 mmHg) is imparted by Class 3b bandages and 3c type bandages impart high compression between 25 and 35 mmHg.[59] The 3d type extra high compression bandages (up to 60 mmHg) are not often used because the very high pressure generated will reduce the blood supply to the skin. It must be stated that approximately 30–40 mmHg at the ankle which reduces to 15–20 mmHg at the calf is generally adequate for healing most types of venous leg ulcers.[60] Compression stockings provide support to treat DVT and varicose veins, and to prevent venous leg ulcers. They are classified as light support (Class 1), medium support (Class 2) and strong support (Class 3).[61]

Table 2.3 Classification of elastic bandages

Class	Bandage type	Bandage function
1	Lightweight conforming	Apply very low levels of sub-bandage pressure and are used to hold dressings in place
2	Light support	Apply moderate sub-bandage pressure and are used to prevent oedema or for the treatment of mixed aetiology ulcers
3a	Light compression	Exert a pressure range of 14–17 mmHg at the ankle
3b	Moderate compression	Exert a pressure range of 18–24 mmHg at the ankle
3c	High compression	Exert a pressure range of 25–35 mmHg at the ankle
3d	Extra high compression	Exert a pressure of up to 60 mmHg at the ankle

© Woodhead Publishing Limited, 2011

Ideal compression bandages

It should be noted that compression bandages may be harmful if not applied properly. They provide high tension as well as high pressure. A thorough assessment involving several criteria is therefore essential before applying a compression bandage on a limb. For example, it is important to consider the magnitude of the pressure, the distribution of the pressure, the duration of the pressure, the radius of the limb and the number of bandage layers. The ability of a bandage to provide compression is determined by its construction and the tensile force generated in the elastomeric fibres when extended. Compression can be calculated by Laplace's law, which states that the pressure is directly proportional to the bandage tension during application and the number of layers applied but inversely proportional to limb radius.[62] The structure of a compression bandage is, therefore, regarded as an important factor in producing a uniform pressure distribution. An ideal compression bandage should:

- Provide compression appropriate for the individual
- Provide pressure evenly distributed over the anatomical contours
- Provide a gradient pressure diminishing from the ankle to the upper calf
- Maintain pressure and remain in position until the next change of dressing
- Extend from the base of the toes to the tibial tuberosity without gap
- Function in a complementary way with the dressing
- Possess non-irritant and non-allergenic properties.

Compression system

Compression can be exerted to the leg either by a single layer bandage or multilayer bandages. In the UK a four-layer bandaging system is widely used whilst in mainland Europe and Australia the non-elastic two-layer short stretch bandage regime is the standard treatment. A typical four-layer compression bandage system comprises padding bandage, crepe bandage, high compression bandage and cohesive bandage. Both the two-layer and four-layer systems require padding bandage (wadding or orthopaedic wool) that is applied next to the skin and underneath the short stretch or compression bandages.

A plaster-type non-elastic bandage, Unna's boot is favoured in the USA. However, compression would be achieved by three-layer dressing that consists of Unna's boot, continuous gauze dressing followed by an outer layer of elastic wrap. It should be realised that Unna's boot, being rigid, is uncomfortable to wear and medical professionals are unable to monitor the ulcer after the boot is applied. Unna's Boot provides a high working pressure when the calf muscle contracts, but very little pressure while the patient is at rest.[63] The high working pressure serves to increase blood flow, while the low resting pressure facilitates deep venous filling. The Unna's Boot is only effective in ambulatory patients and requires constant re-application as the leg volume decreases due to a reduction in oedema.

© Woodhead Publishing Limited, 2011

Used widely in USA, the Unna's Boot system is uncomfortable to wear due to its rigidity and is both expensive and difficult to apply. Short stretch bandages function in a similar manner to the rigid/inelastic Unna's Boot. They consist of 100% high twisted cotton yarns and are applied onto the limb at full extension. Unlike elastic bandages, short stretch bandages firmly hold the calf thereby providing a high working pressure when the patient walks.[64]

A variety of padding bandages are used beneath compression bandages as padding layers in order to evenly distribute pressure and give protection. They absorb high pressure created at the tibia and fibula regions. It will be noticed that the structure of a padding bandage is regarded as an important factor in producing a uniform pressure distribution. Research has shown that the majority of the commercially available bandages do not provide uniform pressure distribution.[65,66]

Relationship between compression and pressure

The main function of a compression bandage is to exert the required level of pressure onto the leg. The ability of the compression bandage to perform this task is determined by its elastic properties. Sub-bandage pressure is a function of the tension induced into the compression bandage during application, the number of layers used, the width of the bandage, and the circumference of the limb. Applying the bandage with a 50% overlap effectively produces two layers, which generates twice the pressure. The principle of compression bandaging is based on the Laplace principle. When a compression bandage is applied at a constant tension on a limb of increasing circumference it will produce a sub-bandage pressure gradient with the highest pressure exerted on the ankle. Therefore, sub-bandage pressure is directly proportional to bandage tension but inversely proportional to limb circumference. The ability of a bandage to maintain sub-bandage pressure is determined by the elastomeric properties of the yarns, the fabric structure, as well as the finishing treatments applied to the fabric.

Ideal pressure

Compression bandages are mostly used during the initial therapy phase where the aim of treatment is to reduce oedema and overcome venous insufficiency. A number of different types of compression bandage systems are commercially available: the bandages are classified as either rigid/inelastic, short stretch, long-stretch or multilayered. The type of fabric construction influences the degree of extensibility that the bandage will have. At some point the bandage will not be able to extend or stretch any further (lock-out) under a predetermined tension. Evidence suggests that a sub-bandage pressure of 35–40 mmHg at the ankle, which gradually reduces to 17–20 mmHg at the knee, is required to overcome venous hypertension and successfully treat venous leg ulcers.[67] A recent study investigated the degree of pressure that is required to narrow and occlude leg veins

© Woodhead Publishing Limited, 2011

when a subject is in different body positions. The authors found that initial narrowing of the veins occurred at a pressure of 30–40 mmHg in both the sitting and standing positions. Complete occlusion of the superficial and deep leg veins occurred at 20–25 mmHg (supine position), 50–60 mmHg (sitting position), and at 70 mmHg (standing position).[68]

Application of bandages

The elastic properties of the bandages help to provide a high recoiling force, which serves to increase venous flow and reduce venous hypertension. In addition, they conform easily around the lower limb and allow for frequent dressing changes. Skill is required to apply compression bandages at the correct tension and to avoid excessive sub-bandage pressures. Application of high sub-bandage pressure on patients with any type of micro-vascular disease can lead to further occlusion and pressure necrosis of these vessels.[69] Some manufacturers supply compression bandages with a series of geometric markers printed onto the bandage surface. The markers assist in the application of a predetermined level of compression by visually distorting when the bandage is stretched to a specific tension. For example, printed rectangles become squares when the correct bandage tension is reached.

In multilayer bandaging system three or four layers of different types of bandage are used to provide external compression. A multilayer system may include a combination of nonwoven padding bandage, inelastic creep bandage, elastic compression bandages and cohesive (adhesive) bandage. The different properties of each bandage type contribute to the overall effectiveness of the bandage system. The elastic bandage component provides sustained compression while the cohesive bandage offers rigidity thereby enhancing calf muscle pump function. The four-layer high compression system developed by a clinical group at Charing Cross Hospital (London) has gained wide acceptance of use in the UK hospitals. The four-layer system was developed specifically to incorporate different bandage types and properties in order to overcome the clinical issues of exudate, protection of bony prominences, and the ability to sustain sub-bandage pressure over a period of time.[70] In addition, the system was designed to apply the required 40 mmHg of pressure at the ankle, overcome disproportionate limb size and shape, and to remain in position on the leg without slippage. Application of the four-layer system involves first applying a padding bandage layer from the base of the toes to just below the knee. A crepe bandage is applied next followed by an elastic compression bandage. Finally, a cohesive layer is applied in order to add durability and to complete the overall pressure profile. Examples of different types of compression bandages, cohesive bandages, padding bandages, and multilayer compression systems are shown in Table 2.4. Multilayer high compression bandage system has been shown to provide a safe and effective treatment option for uncomplicated venous leg ulcers. Ulcer healing rates of up to

© Woodhead Publishing Limited, 2011

Table 2.4 Illustration of bandages used in compression therapy

Bandage name	Function	Manufacturer
Tensopress	Type 3c Long stretch bandage	Smith & Nephew
Setopress	Type 3c Long stretch bandage	Medlock Medical
SurePress	Type 3c Long stretch bandage	ConvaTec
Adva-co	Type 3c Long stretch bandage	Advancis Medical
Dauerbinde K	Long stretch bandage	Lohmann & Rauscher
Silkolan	Type 2 Short stretch bandage	Urgo Limited
Tensolan	Type 2 Short stretch bandage	Smith & Nephew
Comprilan	Type 2 Short stretch bandage	Smith & Nephew
Actiban	Type 2 Short stretch bandage	Activa Healthcare
Actico (Cohesive)	Type 2 Short stretch bandage	Activa Healthcare
Rosidal K	Type 2 Short stretch bandage	Lohmann & Rauscher
Co-Plus	Cohesive bandage	Smith & Nephew
Tensoplus	Cohesive bandage	Smith & Nephew
Coban	Cohesive bandage	3M
Surepress	Padding bandage	ConvaTec
Soffban	Padding bandage	Smith & Nephew
K-soft	Padding bandage	Urgo Limited
Softexe	Padding bandage	Medlock Medical
Advasoft	Padding bandage	Advancis Medical
Flexi-ban	Padding bandage	Activa Healthcare
Cellona	Padding bandage	Lohmann & Rauscher
Ultra-soft	Padding bandage	Robinsons Healthcare
Ortho-band	Padding bandage	Millpledge Healthcare
Formflex	Padding bandage	Lantor (UK) Limited
Profore	Multilayer compression system	Smith & Nephew
Proguide	Multilayer compression system	Smith & Nephew
Ultra Four	Multilayer compression system	Robinsons Healthcare
System 4	Multilayer compression system	Medlock Medical
K-four	Multilayer compression system	Urgo Limited

70% at 12 weeks have been obtained.[71] The four-layer bandaging technique has been shown to heal chronic ulcers that have failed to respond with traditional adhesive plaster bandage systems.[72] A recent review on compression therapy for venous leg ulcers concluded that multilayer compression system is more effective than low compression or single layer compression.

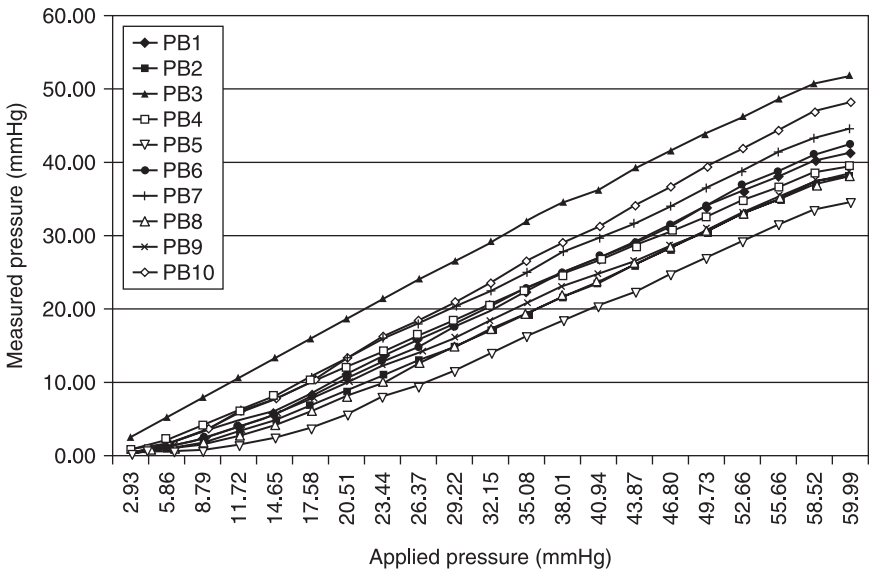
2.4.5 Current problems and novel bandages

During the past few years there have been increasing concerns relating to the performance of bandages especially pressure distribution properties for the treatment of venous leg ulcers. This is because the compression therapy is a complex system and requires two or multilayer bandages, and the performance properties of each layer differ from other layers. The widely accepted sustained graduated compression mainly depends on the uniform pressure distribution of

© Woodhead Publishing Limited, 2011

different layers of bandages in which textile fibres and bandage structure play a major role. The padding bandages commercially available are nonwovens that are mainly used to distribute the pressure, exerted by the short stretch or compression bandages, evenly around the leg, otherwise higher pressure at any one point not only damages the venous system but also promotes arterial disease. Therefore there is a need to distribute the pressure equally and uniformly at all points of the lower limb and this can be achieved by applying an effective padding layer around the leg beneath the compression bandage. In addition, the padding bandages should have the capability to absorb high pressure created at the tibia and fibula regions. Wadding also helps to protect the vulnerable areas of the leg from generating extremely high pressure levels as compared to those required along the rest of the leg. The research carried out at the University of Bolton involving the ten most commonly used commercial padding bandages produced by major medical companies showed that there are significant variations in properties of commercial padding bandages,[73,74] more importantly the commercial bandages do not distribute the pressure evenly at the ankle as well as the calf region (Fig. 2.5).

The integrity of the nonwoven bandages is also of great concern. When pressure is applied using compression bandages, the structure of the nonwoven bandages may collapse and the bandage would not impart cushioning effect to the limb. The comfort and cushioning effect are considered to be essential properties for padding bandages because they stay on the limb for several days.



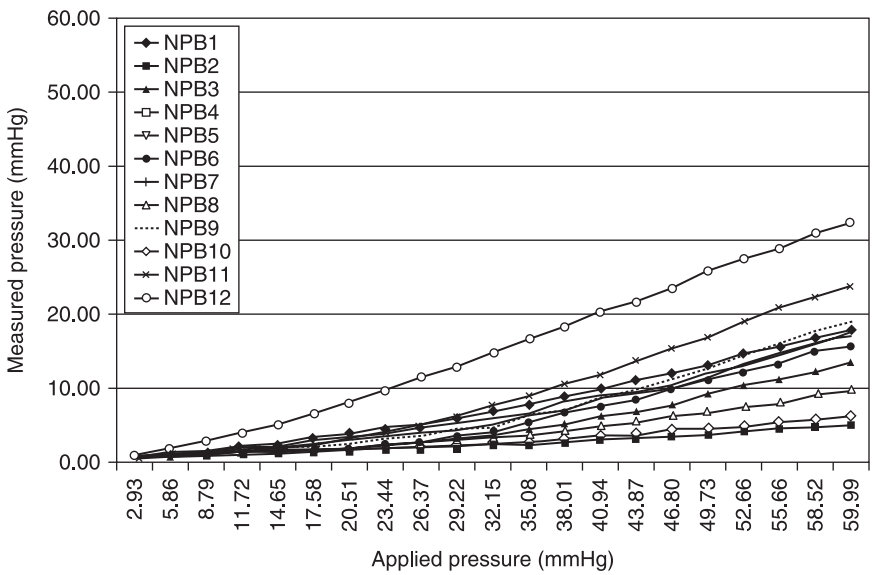
2.5 Pressure distribution of commercial padding bandages.

© Woodhead Publishing Limited, 2011

Twelve padding bandages which consisted of single component fibres, binary blends and tertiary blends incorporating polyester, bicomponent fibres and natural fibres such as cotton and viscose have been designed and developed at the University of Bolton (Table 2.5). The salient properties of the developed bandages are:

- All the developed padding bandages possess suitable bulkiness
- None of the bandages has lower tensile strength or breaking extension that hinders the performance characteristics of an ideal padding bandage
- The tear resistance of bandages, except 100% hollow viscose (NPB5), is high and this means that the bandage cannot be easily torn by hand after wrapping around the leg. However, making perforations at regular intervals across the bandage facilitates easy tearing
- The absorption of solution containing Na^+ and Ca^{2+} ions (artificial blood) is significantly high, irrespective of fibre type and structure
- The rate of absorption of all the developed bandages is also high
- The pressure distribution of all the novel bandages is good up to 60 mmHg (Fig. 2.6).

In the UK, multilayer compression systems are recommended for the treatment of venous leg ulcers.[75] Although multilayer compression bandages are more effective than single-layer bandages in healing venous leg ulcers,[76] it is generally agreed by the clinicians that multilayer bandages are too bulky for patients and the cost involved is high. A wide range of compression bandages is available for the



2.6 Pressure distribution of novel padding bandages.

© Woodhead Publishing Limited, 2011

Table 2.5 Novel padding bandages

Identification	Product	Fibre type	Fibre dtex; length (mm)	Blend ratio (%)	Structure
NPB1	Single component	Polyester	3.3; 40	100	Needlepunched (both sides)
NPB2	Single component	Polyester (bleached)	5.3; 60	100	Needlepunched (both sides)
NPB3	Single component	Hollow polyester	3.3; 50	100	Needlepunched (both sides)
NPB4	Single component	Viscose	3.3; 40	100	Needlepunched (both sides)
NPB5	Single component	Hollow viscose	3.3; 40	100	Needlepunched (both sides)
NPB6	Single component	Lyocell	3.3; 38	100	Needlepunched (both sides)
NPB7	Binary blends	Polyester/viscose	3.3; 40/3.3; 40	75/25	Needlepunched (both sides)
NPB8	Binary blends	Polyester/viscose	3.3; 40/3.3; 40	50/50	Needlepunched (both sides)
NPB9	Binary blends	Polyester/viscose	3.3; 40/3.3; 40	25/75	Needlepunched (both sides)
NPB10	Binary blends	Polyolefin/viscose	2.2; 40/3.3; 40	20/80	Needlepunched (both sides) and thermal bonded
NPB11	Tertiary blends	Polyester/viscose/cotton (bleached)	3.3; 40/3.3; 40/1.8; 22	33/33/33	Needlepunched (both sides)
NPB12	Tertiary blends	Polyester/viscose/ polyolefin	3.3; 40/3.3; 40/2.2; 40	60/25/15	Needlepunched (both sides) and thermal bonded

© Woodhead Publishing Limited, 2011

treatment of leg ulcers but each of them have different structure and properties and this influences the variation in performance properties of bandages. In addition long stretch compression bandages tend to expand when the calf muscle pump is exercised, and the beneficial effect of the calf muscle pump is dissipated. It is a well established practice that elastic compression bandages that have the extension of up to 200% are applied at 50% extension and at 50% overlap to achieve the desired pressure on the limb. It has always been a problem for nurses to exactly stretch the bandages at 50% and apply without losing the stretch from ankle to calf, although there are indicators for the desired stretch (rectangles become squares) in the bandages. The elastic compression bandages are classified (Table 2.3) according to their ability to produce predetermined levels of compression and this has always been a problem to select the right compression bandage for the treatment. The inelastic short stretch bandage (Type 2) system, which has started to appear on the UK market, has the advantage of applying at full stretch (up to 90% extension) around the limb. The short stretch bandages do not expand when the calf muscle pump is exercised and the force of the muscle is directed back into the leg which promotes venous return. The limitations of short stretch bandages are that a small increase in the volume of the leg will result in a large increase in compression and this means the bandage provides high compression in the upright position and little or no compression in the recumbent position when it is not required. During walking and other exercises the sub-bandage pressure rises steeply and while at rest the pressure comparatively drops. Therefore patients must be mobile to achieve effective compression and exercise is a vital part of this form of compression. Moreover the compression is not intact with skin when reduction in limb swelling because the short stretch bandage is inelastic, and it has already been stretched to its full.

In order to address the above problems, a novel nonwoven vari-stretch compression bandage (NVCB) has been designed and developed at the University of Bolton. The principal features of the NVCB are:[74]

- Novel nonwoven technology was used to develop the variable compression bandages. It should be mentioned that no nonwoven compression bandages are listed in the Drug Tariff. In the UK, the availability of wound dressings and bandages for use in patients' homes is dictated by the Drug Tariff.
- The performance and properties of the novel bandages are superior to existing multiplayer commercial compression bandages. This fulfils the requirement of ideal variable pressure from ankle to below knee positions of the limb for the treatment of venous leg ulcers.
- Vari-stretch nonwoven bandages also meet the standards and the tolerances stipulated by BS 7505.[77]

The application of a multilayer bandage system requires expertise and knowledge. Nurses must undergo significant practise-based training in order to develop appropriate bandage application skills needed for multilayer compression

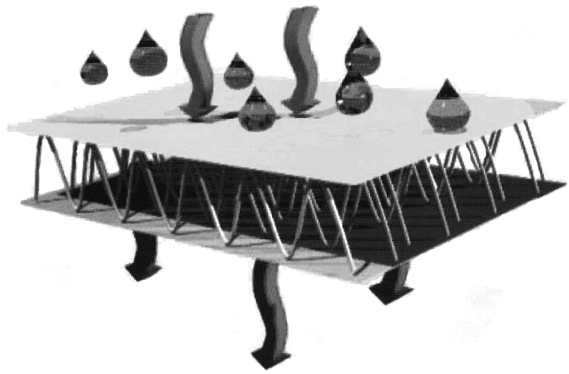
© Woodhead Publishing Limited, 2011

system. Successful bandaging relies upon adopting a good technique in both stretching the bandage to the correct tension and ensuring proper overlap between layers. In addition, nurses need to have knowledge of the different performance properties of each bandage within the multilayer system, and how each bandage combines to achieve safe and adequate compression. The ability of multilayer bandage systems to maintain adequate compression levels for up to one week has reduced the necessity for frequent dressing changes and has therefore, decreased treatment costs. However, the cost of multilayer compression system is still relatively high due to the requirement for a specific bandage for each layer. Tolerance to multilayer compression system is generally good but non-compliance in some patients often results in prolonged or ineffective treatment. Some patients are unable to wear footwear due to the bulkiness of multilayer compression regime. These patients often refuse treatment since the requirement to remain house bound is totally unacceptable. At night patients find compression bandages too uncomfortable and often remove them in order to sleep. Since the application of multilayer compression systems is complex most patients are unable to re-apply the bandages themselves.

2.4.6 Three-dimensional compression bandages

Recently, spacer technology has been increasingly used to produce three-dimensional (3D) materials for technical textiles sectors such as automotive, medical, sports and industrial market. The spacer technology is flexible, versatile, cost effective and an ideal route to produce 3D materials for medical use. It is identified that spacer is the right technology to produce novel compression bandages that meet the prerequisites of both ideal padding and compression bandages. The main reasons for the current interest in 3D spacer fabrics for producing novel compression bandages are several-fold. In 3D spacer fabrics, two separate fabric layers are combined with an inner spacer yarn or yarns using either warp knitting or weft knitting route (Fig. 2.7). The two layers can be produced from different fibre types such as polyester, polyamide, polypropylene, cotton, viscose, lyocell, wool, etc., and can have completely different structures.[78] It is also possible to produce low modulus spacer fabrics by making use of elastic yarns. Elastic compression could be achieved by altering the fabric structure. It should be mentioned that 3D structure allows greater control over elasticity and these structures can be engineered to be uni-directional, bi-directional and multi-directional. Uni-directional elasticity is one of the desired properties for compression bandages. The 3D nature of spacer fabrics makes an ideal application next to the skin[79] because they have desirable properties that are ideal for the human body. 3D fabrics are soft, have good resilience that provides cushioning effect to the body, breathable, ability to control heat and moisture transfer.[78] For venous leg ulcer applications, such attributes together with improved elasticity and recovery promote faster healing. It must be stated that 3D spacer fabrics can

© Woodhead Publishing Limited, 2011



2.7 Illustration of a spacer fabric structure.

also be produced using double-jersey weft knitting machines.[78] The main advantages of weft knitted spacer fabrics over warp knitted fabrics include cost effectiveness because there is no need to prepare a number of warp beams and spun yarns as well as coarser count hairy yarns can be used on weft knitting machines.

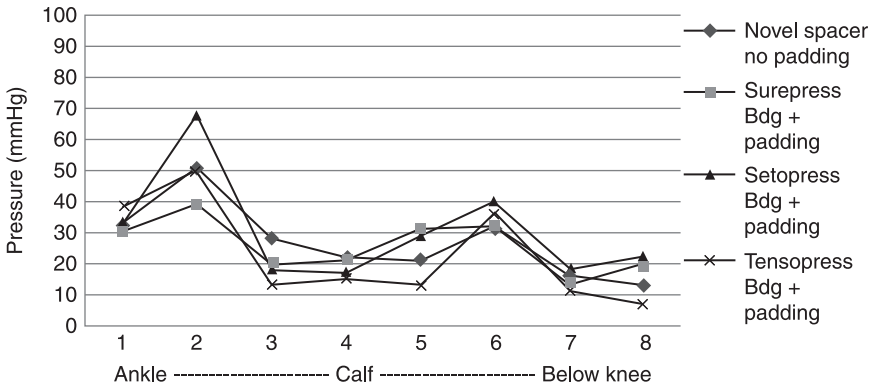
Because of the problems associated with the currently available bandages for the treatment of venous leg ulcers as discussed in Section 2.4.5, it is vital to research and develop an alternative bandaging regimen that meets all the requirements of an ideal compression system.

Three-dimensional single-layer bandage development

A novel single-layer bandage system for the treatment of venous leg ulcers has been designed and developed at the University of Bolton. This 3D knitted spacer bandage has been designed by making use of mathematical modelling and Laplace's law. A specially created 3D computer simulated finite element (FE) model has been used in the design, development and engineering of the 3D novel spacer fabric during this research programme. The predicted tensile properties from the FE computer model in the machine direction of the fabric were compared with the experimental results to verify the model and a reasonable agreement was obtained. These results from the parametric study of the FE model were utilised to design and develop the novel 3D single-layer weft knitted spacer bandage for the treatment of venous leg ulcers. The results indicated that the desirable levels of pressure (compression) would be achieved at a spacer thickness ranging from 1.6–2.9 mm of a weft knitted spacer bandage.

The pressure profile ascertained from the mannequin leg equipment for both the commercial two-layer compression bandage system and the novel single-layer 3D weft knitted spacer bandage clearly showed the desirable gradual reduction of recorded pressure/compression (Fig. 2.8).[80] The recorded measurements

© Woodhead Publishing Limited, 2011



2.8 Pressure profile of novel and commercial bandages.

show average sub-bandage pressure results from relatively high 68 mmHg down to 33 mmHg at the ankle but gradually reducing to 29 mmHg to 11 mmHg below the knee. The novel 3D spacer bandage appears to have achieved desirable comparable results at the 37% stretch with results of 33–51 mmHg at the ankle reducing to 13–16 mmHg below the knee. Therefore when compared with the two-layer commercial compression bandage system, the single-layer novel 3D knitted spacer bandage possesses desirable pressure profile. Prior to the above pressure measurement, the novel single-layer 3D weft knitted spacer bandages were also tested at different stretch to establish the desirable stretch/elongation required to achieve the required graduated compression from the ankle to just below the knee. The result shows that 37% stretch meets the desirable pressure profile.

In order to test the stretch and recovery of the developed 3D spacer bandages, the *British Pharmacopoeia* method 'Extension measurements on stretch bandages' was employed.[81] The bandages are tested on a specific test rig to a force of 1 kg/cm sample nominal width. The novel 3D spacer achieved 151% stretch and a recovery of 93%, within the limits of industrial standards, therefore showing excellent stretch and recovery properties.

The degree of pressure that is transferred onto the leg through the compression bandage is of major importance. It is important that excessive pressure at any one point on the leg is distributed equally and uniformly at all points, especially over vulnerable bony prominences present around the ankle and the front of the leg. The pressure transference measurements taken on the pressure transference apparatus indicate, unlike padding bandage, the commercial spacer fabrics as well as the novel 3D spacer fabric possesses excellent pressure distribution properties.

Pilot user study

A pilot users study was carried out on seven healthy volunteers with no known vascular complications or any other known chronic illnesses. Three women and

© Woodhead Publishing Limited, 2011

four male volunteers of different ages and sizes were recruited for these trials. This trial was carried out to directly compare the developed novel single-layer 3D weft knitted spacer bandage and one of the standard two-layer compression bandage systems. The sub-bandage pressure measurements were made by using Kikuhime pressure measuring device sensors strategically placed on the volunteers' lower limb. Three Kikuhime devices were calibrated in-house prior to application. First a commercial needlepunched nonwoven padding bandage was applied to the limb covering the strategically placed Kikuhime sensors. Then the selected Type 3c compression bandage was applied, this was following the recommended elongation and overlap (50%). The sub-bandage pressure readings were recorded in both; a seated position with the volunteers' foot placed flat against the floor and then in a standing position. This was repeated with the application of the novel 3D weft knitted spacer bandage. The procedure was then again repeated after moving the Kikuhime sensors to down the inside of the lower limb. This pilot study was carried out to ascertain a preliminary assessment of pressure profiles between the developed novel single-layer 3D weft knitted spacer bandage and popular two-layer compression bandage system.

The results from the pilot user study show the sub-bandage pressure readings at the ankle are 40–50 mmHg reducing to 11–18 mm Hg just below the knee. Therefore, pressure readings for both the novel single-layer 3D knitted spacer and the commercial two-layer compression bandage system tested are slightly higher than the recommended at the ankle but both have very similar if not almost the same results.

The novel single-layer compression system simplifies and standardises the application of compression, be more patient friendly, reduces the nursing time and significantly decreases the treatment cost because it replaces the existing multilayer bandage regimes.

2.5 Wound dressing structures

2.5.1 Fibres and yarns used in wound care

Textile fibres used in wound care can be divided into the following categories:

- *Degradable fibres*: such as cotton, viscose rayon, lyocell, silk, wool, bamboo, alginate, chitin and chitosan, collagen, gelatin
- *Non-degradable fibres*: such as polyethylene, polypropylene, polyamide, polyester, polytetraflouroethylene (PTFE), elastomeric fibres
- *Resorbable fibres*: such as polylactic acid (PLA), polyglycolic acid (PGA), polydioxanone (PDS)
- *Speciality medical fibres*: such as activated charcoal fibres, catgut, branan ferulate, super absorbent polymer (SAP)

Yarns used in wound care products can be divided into either staple-fibre yarns or continuous-filament yarns. Other specialised yarns, such as double-covered

© Woodhead Publishing Limited, 2011

elastomeric yarns, core/sheath and side-by-side bicomponent filament yarns are also used in some specialised wound care products.

2.5.2 Fabric structures used in wound care

The following fabric structures are used in wound care products, either on their own, or in combination with other fabric structures to form composites in order to imbibe a multitude of attributes in one composite material. It is also common to combine the following fabrics with films, membranes, coatings, foams, powders, etc., to enhance the properties of the final product.

Woven structures

Woven structures are used for a very wide spectrum of healthcare, medical and surgical products. Woven fabrics are commonly used for gauze dressings, capillary dressings, support and compression bandages, plasters, vascular prostheses, scaffolds for tissue engineering and a wide range of operating room garments, hospital bed linen and staff uniform garments, etc.

Woven fabrics are extremely versatile in terms of the type of yarns and structures that can be engineered on the loom, but suffer from the tendency of fraying when cut into shapes and the anisotropic nature of their properties. The woven structure tends to scissor when extended in the bias direction, which could be detrimental for some applications, such as mattresses for pressure sores and garments for hypertrophic scarring treatment.

Warp and weft knitted structures

Warp and weft knitted fabrics are used for a very wide range of healthcare and medical products and their use in hygiene and medical products has increased steadily over many years. Knitted structures offer many advantages over other type of fabrics, such as flexibility in terms of opacity, stretch and recovery and above all flat, circular and truly three-dimensional and often complete products can be produced directly on the knitting machine.

Warp and weft knitted fabrics are extremely versatile in terms of the width and shape of the products to be produced and are popularly used to manufacture retention, support and compression bandages, vascular prosthesis, stents, ligaments and tendons, surgical hosiery, blankets, wound dressings, stockings, elasticated net structures, pressure garments and spacer fabrics for a wide range of healthcare and medical products to replace rubber, foam, latex and other laminated structures.

Nonwoven structures

Nonwoven structures are used mostly in the manufacture of disposable products. In fact, around 70% of medical products are disposable and this leads to

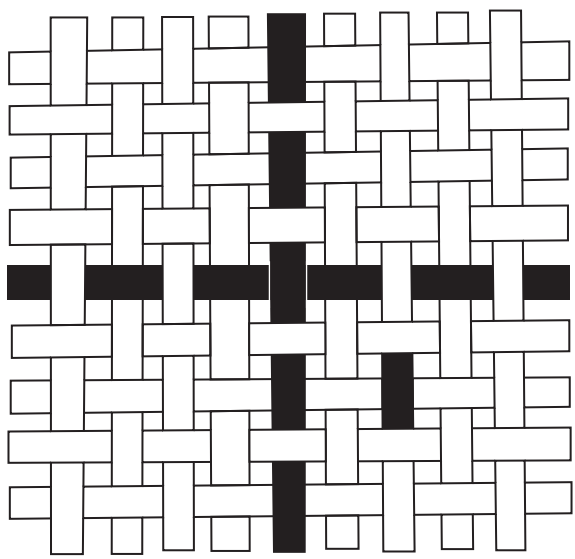
© Woodhead Publishing Limited, 2011

concerns regarding environmental pollution. In spite of these concerns, nonwovens dominate the medical textiles market because they possess a number of desirable properties, such as high absorption, permeability as well as cost effectiveness.

The main type of nonwoven fabric used in healthcare and medical products are drylaid and polymerlaid fabrics. Needlepunched, hydroentangled, thermal bonded, chemical bonded, spunlaid, meltblown and, lately, nanowebs are commonly used. Diapers, feminine sanitary products, incontinence pads, wound dressings, scaffolds for tissue culture, operating room garments, such as surgical gowns, caps, masks, wipes, fleeces, protective clothing and many other products are manufactured from one or more of the above type of nonwoven structures. It is common to combine more than one technology on line to produce products with hybrid or tailor-made properties.

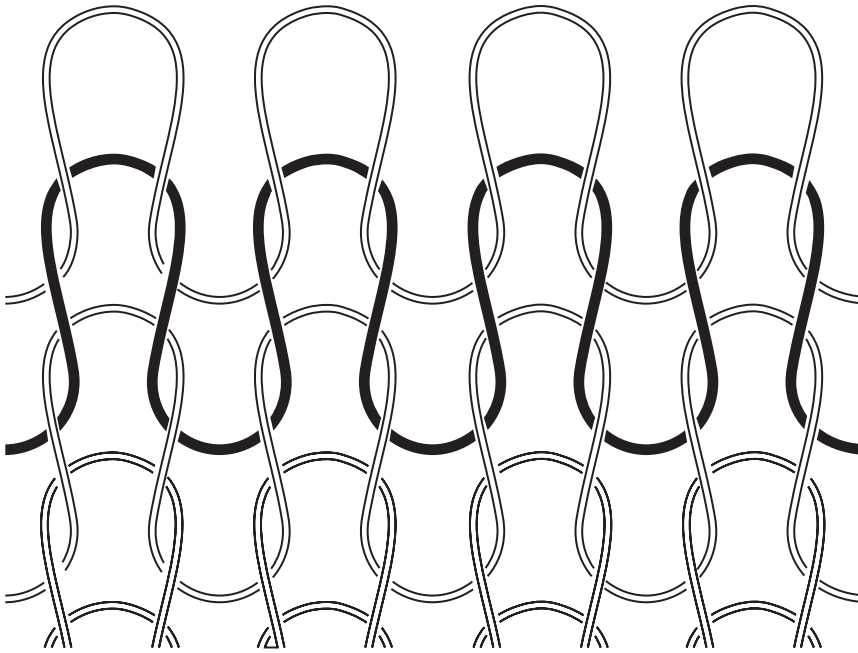
Other types of structures used in medical devices are crochet, which are very similar to warp knitted structures, embroidery and braided structures. In the UK, crochet crepe-type bandages have largely replaced woven crepe bandages in many hospitals. Like warp knitted bandages, crotchet bandages and dressings can be produced in varying opacities and the structure does not fray or split.

The simplest woven, weft knitted, warp knitted and apertured hydroentangled nonwoven structures are illustrated in Figs 2.9 to 2.12, respectively.

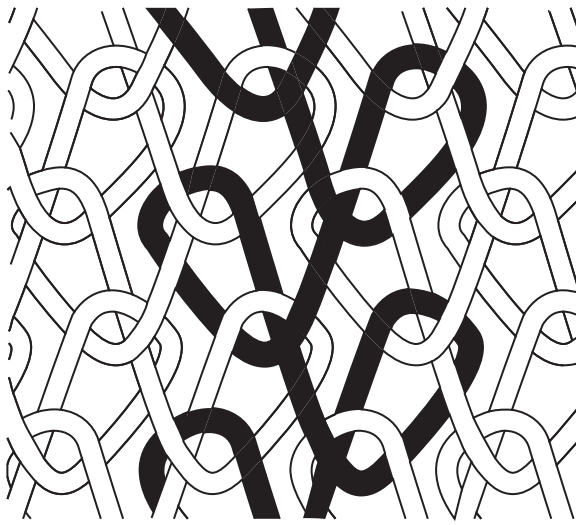


2.9 Woven structure.

© Woodhead Publishing Limited, 2011

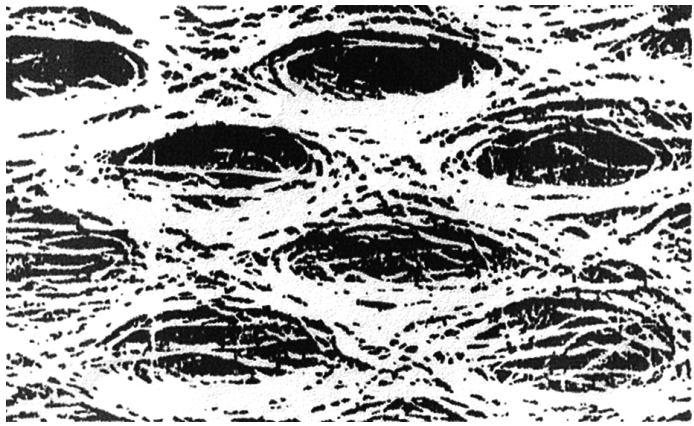


2.10 Weft knitted structure.



2.11 Warp knitted structure.

© Woodhead Publishing Limited, 2011



2.12 Apertured hydroentangled nonwoven structure.

2.5.3 Specifications, manufacture and properties of a range of wound care products and bandages

Non-adherent wound contact layer

A wide range of products are used, which range from fine punched nets made from polyester, polyamide, polypropylene or polyethylene sheet materials, to nonwoven dressings containing gelling and/or antimicrobial fibres, such as alginate, chitosan, carboxy methyl cellulose (CMC) etc. A number of warp and weft knitted products are also used.

One type of such a bandage is described below:

Machine/gauge	Karl Mayer Raschel machine RS4N; E20
Yarn/threading	220 dtex bright viscose rayon filament yarn; full-set; used on both guide bars
Structure	Front guide bar: 0–2/2–0 Back guide bar 0–0/8–8
Run-in per rack	Front guide bar: 1922.7 mm per rack
Back guide bar	2094.7 mm per rack
Finished course per cm	9.6
Finished wales per cm	8.3
Finished fabric width	97 mm
Finished area density	150 g/m^2

A number of bandages are produced across the width of the machine, depending upon the machine width used.

© Woodhead Publishing Limited, 2011

Secondary wound dressing

The main purpose of a secondary dressing is to absorb, retain and diffuse laterally exudate, blood and infectious material exudating from the wound to keep the wound dry and assist in its healing. A wide range of high absorption fibres, such as viscose, cotton and super absorbent polymers/fibres are frequently used in needlepunched and/or hydroentangled nonwoven structures. It is also common to include a microfibre layer, such as spunlaid or meltblown web as a diffusion layer to dissipate the fluid laterally across the dressing to further enhance the absorption properties of these dressings.

Retention bandage

The main purpose of retention bandages is to retain wound dressings in the correct position and avoid contamination of the wound from external sources of infections. The specifications and manufacturing details of a typical retention bandage are given here:

Machine/gauge	Karl Mayer tricot machine; E12
Yarns/threading	Front guide bar: 78 dtex polyamide 6.6 flat filament; full-set
	Back guide bar: 20 tex viscose rayon staple-fibre yarn, waxed; full-set
Structure	Front guide bar: 0–1, 1–0
	Back guide bar: 0–0, 3–3
Run-in per rack	Front guide bar: 4998 mm per rack
	Back guide bar: 2736 mm per rack
Finished courses per cm	>2.4
Finished wales per cm	>0.45
Finished area density	>26 g/m^2

Fabric width tested after 24 h relaxation:

Bandage width	Range
2.5 cm	1.9–2.5 cm
5 cm	4.7–5.3 cm
7.5 cm	6.9–7.7 cm
10 cm	9.4–10.2 cm
15 cm	14.5–15.5 cm

Support bandage

Support bandages provide retention and prevent the development of a deformity or change in shape of a mass of tissue due to swelling or sagging. These can be either flat, tubular or shaped bandages and can be used either on their own, or as a part of a series of bandages for the management of venous leg ulcers.

© Woodhead Publishing Limited, 2011

The specifications and manufacturing details of a woven support bandage, Profore No. 2 Flow Wrapped Bandage, 10 cm wide × 3 m long, sterilised, are given here:

Loom specifications	Bonas 2/110 or 2/175
Number of heald shafts	2
Latch needle type	7762G07
Front reed gauge	7.2 dents per cm
Yarn specifications	Warp: Beams 1 and 2; 2/78 dtex textured polyamide filament twisted with 20 tex ecru cotton, 125 turns per metre
Weft	36.9 tex (1/16 Ne) unbleached cotton yarns
Catch thread	1/44 dtex/13 filaments polyamide yarn
Weave	Plain
Ends per bandage	152
Picks per cm	7.0 ± 2
Fabric width	10 cm
Fabric area density	80 g/m^2
Cut length	3.0 m
Stretched length	4.5 m
Bandage performance	BS 7505: 1995
Bandage type	Type 2
Tension ratio (%), *S*	= 40
Working extension (%), *E*	= 20
Differential extension factor (%), *F*	= 1.5

Compression bandage

Compression bandages are employed mainly for the treatment of varicose veins, deep vein thrombosis and venous leg ulcers. They can be Types 3a, 3b, 3c or 3d depending upon the sub-bandage pressures developed at the ankle. These can vary between 14 mm Hg to 60 mm Hg, depending upon the type of treatment required. For the Sure Press High Compression Bandage (Type 3c) the specifications are:

Machine	Comez Crochet Machine Gauge
Yarn/threading/structure	E20 (20 needles per inch)
Knitting bar	(Front guide bar) Polyamide textured filament and bare Lycra combined together; full-set; closed pillar stitch (1–0, 1–0); one centre yellow polyamide yarn
Laying-in bars	Bar-2: One yellow polyamide yarn; 1–1/0–0/(6–6/5–5) × 7/6–6 (0–0/1–1) × 4/0–0

© Woodhead Publishing Limited, 2011

	Bar-3: One yellow polyamide yarn; 0–0/16–16/(0–0/1–1) × 7/0–0/16–16/(0–0/1–1) × 4 Bar-4: Cotton/viscose staple-fibre yarn; two ends per guide; 1 in, 1 miss (half-set); 0–0/5–5
Bandage performance	BS7505: 1995
Tension ratio (%), *S*	= 85
Working extension (%), *E*	35–150
Differential extension factor (%), *F*	= 4

Flight socks

Flight socks are used mainly during long distance flights when passengers are sitting in confined spaces in one position for long periods. The lack of exercise, mainly foot and ankle movements, causes venous return from the foot to the heart to slow down, as the blood has to be pumped from the lower leg to the heart against the force of gravity. This lack of venous return causes blood clots, which is termed deep vein thrombosis.

The production details are given below:

Machine type	Pendolina Shark or Sanjachimo Star
Machine diameter	4 inches
Machine gauge	E10.5 (132 needles)
Yarn type and linear density	Polyamide (black) textured filament yarn 380 dtex Lycra (laid-in yarn) 185 dtex Lycra (plating yarn) 44 dtex
Lycra feed	Infinitely variable positive feed for laid-in Lycra yarn to achieve variable compression from the ankle to the end of the sock (just below the knee)
Compression levels	Ankle: 14–17 mmHg Calf: 12–15 mmHg Below knee: 10–13 mmHg

2.6 Conclusions

The chapter provides an insight into the physiology of wounds, various dressings and the management of different kinds of wounds. Successful wound management requires a careful selection of wound dressing which is crucial for medical

© Woodhead Publishing Limited, 2011

personnel as each and every type of wound needs appropriate dressing. Treatment of venous leg ulcers requires careful clinical consideration in order to determine the correct care regime. Often the first course of action is to debride the wound so that infection is minimised and wound healing is stimulated. The presence of bacteria in wounds can severely impair healing and hinder the formation of healthy tissue. Therefore, suitable antimicrobial dressing enhances the wound healing process. Wound dressings have several important functions to perform throughout the entire treatment phase. In the initial stage dressings are required to remove and absorb exudate, to provide a moist and warm wound environment to promote healing, and to prevent bacterial infection. Once new granulated tissue has formed different types of dressings may be used to simply protect the wound area from damage. Advances in bio-engineering and bio-chemistry have resulted in new treatments becoming available for various wounds. Bio-engineered skin contains various growth factors and proteins that help to encourage and increase wound healing. Cloned growth factors from specific proteins are now available and research studies continue to determine their effectiveness in accelerating wound healing. Continued research and innovation provides evidence that these new technologies are effective for better wound management. Currently, innovations mainly come from large textile medical devices companies which have their own research and development departments. However, many novel wound dressing products continue to be developed by small and medium size companies, albeit largely through collaboration with universities and other allied research establishments.

An extensive literature and many commercial wound dressings and bandages have been cited in this chapter and these would be a 'ready reckoner' for the readers to understand the multidisciplinary subject areas of wounds as well as textile-based wound dressing medical devices.

2.7 References

1 Bennett G, Dealey C *et al*. (2004). The cost of treating pressure ulcers in the UK. *Age Ageing*, 33, 230.
2 Roberts, S (2007). *Working Together for Better Diabetes Care*. Publication No 281799, Department of Health (DoH), London. May 2007.
3 Morrell C J *et al*. (1998). Cost effectiveness of community leg ulcer clinics: randomised controlled trial. *BMJ*, 316, 1487.
4 Falabella A F (1999). Debridement and management of exudative wounds. *Dermatol Ther*, 9, 36–43.
5 Maklebust J (1996). Using wound care products to promote a healing environment. *Crit Care Nurs Clin North Am*, 8(2), 141–158.
6 Tallon R W (1996). Wound care dressings. *Nurs Manage*, 27(10), 68–70.
7 Falabella A F, Carson P, Eaglstein W H *et al*. (1998). The safety and efficacy of a proteolytic ointment in the treatment of chronic ulcers of the lower extremity. *J Am Acad Dermatol*, 39(5, pt 1), 737–740.
8 Steed D L (2004). Debridement. *Am J Surg*, 187(5, suppl. 1), 71S–74S.

© Woodhead Publishing Limited, 2011

9 O'Brien M (2003). Methods of debridement and patient focused care. *J Community Nursing* 17(11), 17–25.
10 Wang J, Wang S, Zhao G, Wang, Z, Lineaweaver W C and Zhang F (2006). Treatment of infected wounds with maggot therapy after replantation. *J Reconstr Microsurg*, 22(4), 277–279.
11 Steenvoorde P, Budding T and Oskam J (2005). Determining pain levels in patients treated with maggot debridement therapy. *J Wound Care*, 14(10), 485–488.
12 Steenvoorde P, Jacobi C E and Oskam J (2005). Maggot debridement therapy: free-range or contained? An in-vivo study. *Adv Skin Wound Care*, 18(8), 430–435.
13 Sherman R A (2003). Maggot therapy for treating diabetic foot ulcers unresponsive to conventional therapy. *Diabetes Care*, 26(2), 446–451.
14 Reschreiter H, Wong P and Kapila A (2004). An understimated tool in wound care? Biosurgery, the use of larval therapy. *Care Crit Ill*, 20(6), 189–192.
15 Anon (1991). Local applications to wounds–II: dressings for wounds and ulcers. *Drug Ther Bull*, 29(25), 97–100.
16 Bolton L L, Johnson C L and Rijswijk L V (1992). Occlusive dressings: therapeutic agents and effects on drug delivery. *Clin Dermatol*, 9(4), 573–583.
17 Rajendran S and Anand S C (2002). *Developments in Medical Textiles, Textile Progress*. The Textile Institute, Manchester, 32, 4.
18 Foster L, Moore P and Clark S A (2000). A comparison of hydrofibre and alginate dressings on open acute surgical wounds. *J Wound Care* 9, 442–445.
19 Lawrence I G, Lear J T and Burden A C (1997). Alginate dressings and the diabetic foot ulcer. *Pract Diabetes Int*, 14, 61.
20 Suzuki Y, Tanihara M, Nishimura Y, Suzuki K, Yamawaki Y, *et al.* (1999). In vivo evaluation of a novel alginate dressing. *J Biomed Mater Res*, 48, 522.
21 Donaghue V M, Chrzan J S, Rosenblum B I, Giurini J M, Habershaw G M and Veves A (1998). Evaluation of a calcium–alginate wound dressing in the management of diabetic foot ulcers. *J Prevent Heal*, 11, 114.
22 Torres-de-Castro O G, Carlos A G, Torra-i-Bou (1997). Pure calcium–sodium alginate dressing. Multicenter evaluation of chronic cutaneous lesions. *Revista de Enfermeria*, 20, 23.
23 McMullen D (1991). Clinical experience with a calcium alginate dressing. *Dermatol Nurs/Dermatol Nurs Assoc*, 3, 219.
24 Berry D P, Bale S and Harding K G (1996). Dressings for treating cavity wounds. *J Wound Care*, 5, 10.
25 Bettinger D, Gore D and Humphries Y (1995). Evaluation of calcium alginate for skin graft donor sites. *J Burn Care Rehabil*, 16, 59.
26 Ingram M, Wright T A and Ingoldby C J (1998). A prospective randomized study of calcium alginate (Sorbsan) versus standard gauze packing following haemorrhoidectomy. *J R Coll Surg Edinburgh*, 43, 308.
27 Davey R B, Sparnon A L and Byard R W (2000). Unusual donor site reactions to calcium alginate dressings. *J Int Soc Burn Injuries* 26, 393.
28 Lin S S, Ueng S W, Lee S S, Chan E C, Chen K T, *et al.* (1999). In vitro elution of antibiotic from antibiotic-impregnated biodegradable calcium alginate wound dressing. *J Trauma*, 47, 136.
29 Anon (1997). Lyocell-based fibre to replace alginate in wound dressing. *Med Textiles*, 4, 2.
30 Anon (1989). Protective dressing designed for minor wounds. *Med Textiles*, 7, 7.

© Woodhead Publishing Limited, 2011

31 Stone C A, Wright H, Devaraj V S, Clarke T and Powell R (2000). Healing at skin graft donor sites dressed with chitosan. *Br J Plast Surg*, 53, 601.
32 Biagini G, Bertani A, Muzzarelli R, Damadei A, DiBenedetto G, *et al.* (1991). Wound management with *N*-carboxybutyl chitosan. *Biomaterials*, 12, 281.
33 Muzzarelli R (1995). Methylpyrrolidinone chitosan, production process and uses thereof. US Patent 5 378 472.
34 Williams C (1995). Mepitel. *Br J Nurs*, 4, 51.
35 Thomas S (1994). Low adherence dressings. *J Wound Care* 3, 27–30.
36 Thomas S. *Wound Management and Dressing*, Pharmaceutical Press, London 1990.
37 Hollinworth H. Developing a nursing strategy to change woundcare practice, Poster presented at the 5th Clinical Nurse Specialism Conference, Kensington, London 2000.
38 Hollinworth H. Overcoming Confusion; Selecting Dressings that Minimise Wound Pain and Tissue Trauma, Independent Survey leaflet, Ipswich 2000.
39 Rajendran S and Anand S C (2002). Insight into the development of non-adherent, absorbent dressings. *J Wound Care*, 11, 191.
40 Bowler P G, Davies B J and Jones S A (1999). Microbial involvement in chronic wound malodour. *J Wound Care*, l8, 216.
41 Williams K and Elizabeth G (1999). Malodorous wounds: causes and treatment. *Nurs Resident Care*, 1, 276.
42 Thomas S and McCubbin P (2003). An in vitro analysis of the antimicrobial properties of 10 silver-containing dressings. *J Wound Care*, 12, 420.
43 Moore O A, Moore R A, Smith L A, Campbell F, Seers K and McQuay H J (2001). Systematic review of the use of honey as a wound dressing. *BMC Complement Alt Med*, 1, 2.
44 Martson W A, Carlin R E, Passman M A *et al.* (1990). Healing rates and cost efficacy of outpatient compression treatment for leg ulcers associated with venous insufficiency. *J Vasc Surg*, 30(3), 491–498.
45 Sarkar P K and Ballentyne S (2000). Management of leg ulcers. *Postgrad Med J*, 76, 674–682.
46 Margolis D J, Bilker W, Santanna J *et al.* (2002). Venous leg ulcer: Incidence and prevalence in the elderly. *J Am Acad Dermatol*, 46(3), 381–386.
47 Valencia I C, Falabella A, Kirsner R S *et al.* (2001). Chronic venous insufficiency and venous leg ulceration. *J Am Acad Dermatol*, 44(3), 401–424.
48 Moffatt C J, Franks P J, Doherty D C *et al.* (2004). Prevalence of leg ulceration in a London population. *QJM*, 97(7), 431–437.
49 Nicholaides AN (2000). Investigation of chronic venous insufficiency: a consensus statement (France, March 5–9, 1997). *Circulation*, 102(20), E126–E163.
50 Reichenburg J and Davis M (2005). Venous ulcers. *Semin Cutan Med Surg*, 24(4), 216–226.
51 Zimmet S E (1999). Venous leg ulcers: Modern evaluation and management. *Dermatol Surg*, 25(3), 236–241.
52 Franks P J, Moffatt C J, Connolly M *et al.* (1994). Community leg ulcer clinics: effect on quality of life. *Phlebology*, 9(2), 83–86.
53 Reichenburg J and Davis M (2005). Venous ulcers. *Semin Cutan Med Surg*, 24(4), 216–226.
54 Sibbald R G (1998). Venous leg ulcers. *Ostomy Wound Manage*, 44(9), 52–64.
55 Callam M J, Ruckley C V, Harper D R *et al.* (1985). Chronic ulceration of the leg: extent of the problem and provision of care. *BMJ (Clin Res Ed.)*, 290(6485), 1855–1856.

© Woodhead Publishing Limited, 2011

56 McGuckin M, Stineman M, Goin J *et al*. (1996). Draft guideline: diagnosis and treatment of venous leg ulcers. *Ostomy Wound Manage*, 42(4), 48–78.
57 Mani R, Regan F *et al*. (1995). Duplex ultrasound scanning for diagnosing lower limb deep vein thrombosis. *Dermatol Surg*, 21(4), 324–326.
58 Vowden P and Vowden K (2001). Investigations in the management of lower limb ulceration. *Br J Nurs*, 4,(The Profore Suppl), 627.
59 Cullum N (2002). Compression for venous leg ulcers. *Cochrane Review*, The Cochrane Library, Oxford.
60 Simon D and McCollum C N (1996). Approaches to venous leg ulcer care within the community: compression, pinch skin grafts and simple venous surgery. *Ostomy Wound Manage*, 42, 34.
61 Veraat J C, Pronk G and Neuman H A (1992). Pressure differences of elastic compression stockings at the ankle region. *Dermatol Surg*, 23(10), 935–939.
62 Ramelet A A (2002). Compression therapy. *Dermatol Surg*, 28, 6.
63 Partsch H (1991). Compression therapy of the legs: a review. *J Dermatol Surg Oncol*, 17(10), 799–805.
64 Hampton L (1997). Venous leg ulcers: short stretch bandages for compression therapy. *Br J Nurs*, 6(17), 990–998.
65 Anand S C and Rajendran S (2006). Effect of fibre type and structure in designing orthopaedic wadding for the treatment of venous leg ulcers, in *Medical Textiles and Biomaterials for Healthcare*, ed. by Anand S C, Kennedy J F, Miraftab M and Rajendran S., Woodhead Publishing, Cambridge, 243.
66 Rajendran S and Anand S C (2003). Design and development of novel bandages for compression therapy. *Br J Nurs*, 11, 1300.
67 Stemmer R (1969). Ambulatory-elasto-compressive treatment of the lower extremities particularly with elastic stockings. *Derm Kassenarzt*, 9, 1–8.
68 Partsch B and Partsch H (2005). Calf compression pressure required to achieve venous closure from supine to standing positions. *J Vasc Surg*, 42(4), 734–738.
69 Simon D A, Freak L, Williams I M *et al*. (1994). Progression of arterial disease in patients with healed venous ulcers. *J Wound Care*, 3(4), 179–180.
70 Moffatt C J and Dickson D (1993). The Charing Cross high compression four-layer bandaging system. *J Wound Care*, 2(2), 91–94.
71 Nelzen O, Bergqvist D and Lindhagen A (1991). Leg ulcer etiology–a cross sectional population study. *J Vasc Surg*, 14(4), 557–564.
72 Buchbinder D, McCullough G M and Melick C F (1993). Patients evaluated for venous disease may have other pathological considerations contributing to symptomatology. *Am J Surg*, 166, 211–215.
73 Rajendran S and Anand S C. Development of Novel Bandages for Compression Therapy, Wounds UK 2002, Harrogate, 19–20 November 2002.
74 Rajendran S and Anand, S C. Evaluation of Novel Bandages for Compression Therapy, Wounds UK 2003, Harrogate, 11–12 November 2003.
75 Cullum, N, Fletcher A, Semlyen A and Sheldon T A (1997). Compression therapy for venous leg ulcers, *Qual Health Care*, 6(4), 226–231.
76 Nelson E A, Prescott R J, Harper D R *et al*. (2007). A factorial, randomized trial of pentoxifylline or placebo, four-layer or single-layer compression, and knitted viscose or hydrocolloid dressings for venous ulcers. *J Vasc Surg* 45, 134–141.
77 British Standards. Specification for the elastic properties of flat, non-adhesive, extensible fabric bandages. BS 7505. 1995.
78 Anand S C (2003). Spacers—At the Technical Frontier. *Knit Int*, 10, 38–41.

© Woodhead Publishing Limited, 2011

79 Anon (2002). Spacer Fabric Focus. *Knit Int*, 109, 20–22.
80 Lee G, Rajendran S and Anand S C (2009). New single-layer compression bandage system for chronic venous leg ulcers. *Br J Nurs*, 18(15, Tissue Viability Suppl), S4–S18.
81 Anon (1993). *Extension Measurement on Stretch Bandages*. British Pharmacopeia, TSO, Norwich.

© Woodhead Publishing Limited, 2011

3

Reusable medical textiles

H. M. ZINS, Howard M. Zins Associates LLC, USA

Abstract: Beginning with an historical background, tracing the origins of reusable healthcare textiles and their contribution to the development of the sterile field, the overview details products used in the twenty-first century. Surgical packs and their components, protective apparel and incontinence materials are discussed, among other medical textile products. Physical properties and performance characteristics of various reusable items are outlined for numerous products. Factors related to the environment and health and safety issues are also discussed. The chapter offers a broad coverage of reusable medical textiles for both experienced readers and those new to the subject.

Key words: antimicrobial products, bed sores, coated fabrics, continuous batch washers, fluoropolymers, healthcare costs, incontinence products, laminated fabrics, laundering, life cycle assessment, medical waste incineration, personal protective equipment, sheeting materials, steam sterilization, surgical drapes, surgical accessories, underpads.

3.1 Introduction

This chapter attempts to offer details which will inform the reader concerning key aspects of reusable medical textiles. This will include an historical background concerning the subject and the current products available within today's healthcare sector along with many environmental, human health, regulatory and cost factors impacting upon global society.

3.2 The role of reusable medical textiles: a historical perspective

Reusable textiles and their use in the medical field can be traced to the initial work of Florence Nightingale in her attempt to maintain a hygienically clean environment for patients and in hospitals. This effort eventually led to the introduction of a concept which came to be known as the sterile field, maintained during surgical procedures. Nightingale, beginning with her efforts during the Crimean War, was convinced of 'the crucial importance of sanitary doctrines, and of the deadly consequences of overlooking or ignoring them' (Bostridge, 2008).

As early as the seventeenth century, the Dutch microscopist Anton van Leeuwenhoek studied microorganisms in an attempt to disprove the theory of spontaneous generation. This is the concept that living organisms could suddenly

© Woodhead Publishing Limited, 2011

grow out of inanimate materials such as soil or decaying plants or animals, and cause disease (Grady and Tabak, 2006).

Late in the nineteenth century, the work of many scientists led to the establishment of the germ theory of contagious disease. This is the premise that different microbes, such as bacteria or viruses may cause a specific disease. Many individuals contributed to the establishment of this theory. The work of Robert Koch and Louis Pasteur were particularly notable in this development (McGrath, 1999).

Building on the germ theory, physician and surgeon, Joseph Lister (1827–1912) attempted to determine if he could take certain steps which might decrease the number of deaths during and post surgery. Lister sprayed the operating room with a fine mist of carbolic acid. He theorized that this would kill microbes, but would not harm the patients. Lister also washed his surgical instruments before use and introduced the practice of having the surgical staff wear clean aprons and surgical gloves. Hand washing before surgery was also introduced.

The methods (introduced by Lister) reduced the number of postoperative deaths significantly and initiated the era of antiseptic surgery (Grady and Tabak, 2006). The methodology clearly was the beginning of many improvements in surgery, which led to the modern sterile field in surgery.

Today strict guidelines are in place and maintained to assure that a sterile field indeed is maintained during surgery. This includes procedures such as the assembly and sterilization of an O.R. pack. The utilization of specifically engineered products is also a key element in this methodology. Included are surgical gowns, wraps and drapes which will be discussed later in this chapter (Hogan *et al*., 2003).

3.3 Advantages of reusable textiles

Reusable textiles offer society many advantages. These include environmental, public health and physical property and performance benefits which will be discussed within this section of Chapter 3. Cost advantages are also a major consideration in this study and will be addressed in section 3.6, later in this chapter.

3.3.1 Environmental advantages

Waste generation has been a growing global concern. In the United States alone, waste generation has grown from151.6 million tons in 1980 to 251.3 million tons in 2006 (U.S. Census Bureau, 2008).

The European Textile Service Association (ETSA) Life Cycle Assessment (LCA) study

The European Textile Services Association funded a Life Cycle Assessment (LCA) study. The program was completed in 2000 and was conducted by Teknik Energy & Environment, located in Denmark. The evaluation reviewed the environmental impact of both reusable and disposable surgical gowns. The study

© Woodhead Publishing Limited, 2011

considered a number of environmental impact categories. These included energy consumption, acidification (of water and soil), eutriphication (nutrient discharged to the water environment), global warming and post-consumer waste.

The ETSA life cycle assessment was overseen by an independent critical review panel and based on ISO standards. A number of different reusable and single use disposable surgical gowns were evaluated. In the overall comparison, it was found that reusable products demonstrated the least negative impact on the environment (Schmidt, 2000).

University of Minnesota

A Life Cycle Assessment (LCA) study was conducted by MnTAP (Minnesota Technical Assistance Program). The LCA compared disposable and reusable gowns at Fairview Medical Center, a 2000-bed hospital. The LCA found that reusable products resulted in a waste reduction of 254 000 lbs/year. This also resulted in a cost savings of $360 000/year.

Additional advantages found with the utilization of reusable gowns were 10 times less carbon dioxide emissions relative to disposable products. The LCA also found 20 times less carcinogenic emissions with reusable gowns when compared to disposable products. No differences in infection prevention attributes were found between the reusable and disposable materials (Zimmer, 2009).

U.S. Environmental Protection Administration (EPA)/American Hospital Association (AHA) agreement

The AHA (American Hospital Association) and the U.S. Environmental Protection Administration (EPA) have signed a Memorandum of Understanding (MOU) designated as 'Hospitals for a Healthy Environment'. The agreement recognizes that U.S. hospitals annually generate millions of tons of waste. The MOU designates that by 2005, a 33% reduction of waste volume shall have been achieved. A 50% reduction in waste volume was targeted for 2010. Efforts are continuing to identify realistic strategies to meet the terms of the agreement. One possible route may be to reduce the reliance of hospitals on disposable products (Lord, 1998).

'Hospitals for a Healthy Environment' has recently evolved into a program entitled 'Practice Greenhealth'. The initiative claims to be 'the nation's leading membership and networking organization for institutions in the healthcare community that have made a commitment to sustainable, eco-friendly practices' (Practice Greenhealth).

3.3.2 Public health advantages

There was a brief period which lasted roughly through the 1950s and 1960s during which medical science demonstrated remarkable advances. How reusable medical textiles related to the opportunities and challenges of this phenomenon will be outlined in this section.

© Woodhead Publishing Limited, 2011

Opportunities

Factors such as open heart surgery brought hope to millions of coronary patients, worldwide, previously destined to bleak prospects for recovery. Lifestyle changes such as healthy diets and a regimen of exercise were urged by healthcare specialists, as were the avoidance of tobacco and drugs (Harding, 2000). In addition, the introduction of advanced antibiotics created the impression, and to some extent the reality, that infectious disease could be vanquished by a wide array of highly effective medications (Lesch, 2007). This brief era of optimism came to an unfortunate end during the closing decades of the twentieth century with the introduction of HIV (AIDS) across the globe (Levy and Fischetti, 2003).

Challenges

HIV/AIDS has become a global pandemic within the last several decades. Other diseases including hepatitis B, hepatitis C and a return of TB all threaten world health. SARS, Ebola and many other viruses continue to pose ongoing threats to world health. In addition, bioterrorism continues to pose a potential threat to the civilized world. The anthrax attacks in Washington D.C. during 2001 revealed how vulnerable the United States (and all nations) is to terrorists who might elect to strike with deadly organisms (Levy and Fischetti, 2003).

Connection between waste and human health

A number of studies have indicated the strong possibility that residents near waste landfill sites experience higher levels of disease. Statistically significant increases in cancers of the bladder and leukemia in women have been found in some studies. Other evaluations indicated malformations of the nervous system as well as of the musculoskeletal system (Vrijheide, 2000).

A study in Montreal, Quebec has found increased occurrences of both low birth weight and preterm births born to women residing near solid waste landfill sites (Goldberg *et al*., 1995). At the same Montreal site, additional studies disclosed higher than expected cases of cancer of the liver, stomach, prostate and lungs in men. Women in the same study were found to have higher rates of stomach cancer and cervical uteri cancer (Goldberg *et al*., 1999). An additional study, carried out in Wales (UK) indicated a possible link between residence adjacent to waste landfill sites and congenital abnormalities (Palmer *et al*., 2005).

Medical waste incinerators (MWIs)

As an alternative to waste taken to landfill sites for dumping, hospitals and other health care facilities have also used medical waste incinerators (MWIs). The U.S. EPA has studied MWIs and determined that within their emissions are found high levels of dioxins, furans, carbon monoxide and heavy metals. The EPA also

© Woodhead Publishing Limited, 2011

Table 3.1 EPA Medical Waste Incinerators (MWI) Final Rule

Guideline/cost	Requirements
Guidelines and standards	
Air emission guidelines	Existing MWIs (built on, or before, 20 June 1996)
Air emission standards	New MWIs (built after 20 June 1996)
EPA cost estimates	
Air emission guidelines	$60 million to $120 million, annually
Air emission standards	$12 million to $26 million, annually

disclosed that these contaminants have serious health consequences to populations residing in areas near MWIs (EPA, 1995).

As a result of the EPA findings a final rule for MWIs was issued in 1997. As shown in Table 3.1, these include guidelines and emission standards, as well as cost estimates made by the EPA for following the rule. The EPA estimates that the guidelines and standards will reduce emissions from MWIs by 95% (EPA, 1997).

Threat to healthcare workers

The growing challenge of infectious disease worldwide, referred to previously, indeed impacts negatively on the total population across the Earth. More specifically, the issue poses a direct threat to our society's healthcare workers, charged with the responsibility for treating the sick.

The World Health Organization (WHO) has reported that within the six regions of the globe, which they have identified, there are some 59 million healthcare workers. Depending on their specific responsibilities, nearly all of these individuals are threatened, to some degree, by infectious disease (WHO, 2006).

The U.S. government. under the responsibility of the Occupational Health and Safety Administration (OSHA, 1991), has introduced guidelines known as the Occupational Exposure to Bloodborne Pathogens Rule (OSHA). Governments around the world have issued similar regulations. Primarily, these regulations deal with procedures designed to prevent the transmission of disease to healthcare workers by viral penetration. Use of personal protective equipment (PPE), such as surgical and precaution gowns, are among the guidelines outlined in the OSHA rule. These products will be discussed later in this chapter.

Risk to children

A study pursued by specialists at the Mount Sinai School of Medicine, New York, evaluated the effects of environmentally caused endocrine disrupters on the health of children. Endocrine disrupters (EDs) may alter feedback loops in the brain, pituitary, gonads, thyroid and other components of the endocrine system (Landrigan *et al*., 2003).

© Woodhead Publishing Limited, 2011

Risk to the elderly

An additional report in *Environmental Health Perspectives*, 'Toward a new understanding of Aging', outlined that the increasing numbers of an aging population are also at risk from environmental factors. The study disclosed that exposure to toxicants can increase the risk of diseases common to the elderly such as osteoporosis, hypertension, renal impairment, Parkinson's disease and Alzheimer's disease (Hood, 2003).

Implications of waste and infectious disease within our society

As shown in the preceding section many groups within the world's population are exposed to both the toxic by-products of waste and infectious disease. Reusable healthcare textile products can offer a positive response to these issues. Reused for 40, 50 or more cycles reusable materials are not carted off to landfills, or medical waste incinerators on a daily basis. In addition, reusable protective products offer fluid resistant benefits to healthcare workers and these products are also reused. A significantly lower incidence of waste is exposed to the environment with the utilization of reusable healthcare textile materials.

3.3.3 Physical properties and performance

There are a number of performance factors important with regard to reusable textile materials. Some of these are general, applicable broadly to many products. Others relate to specific applications. Certain broad factors will be described within this section and individual physical properties will be described later in this chapter, where particular products are described.

Ability to recycle

As previously disclosed in this chapter, the recyclability of reusable products offers many environmental and public health advantages relative to the well being of our global society. The millions of tons of medical waste created by single use, disposable materials can, to a great extent, be significantly reduced, as reusable medical textiles may be used. Certainly, the utilization of medical waste incineration and hazardous waste landfills can be diminished as fewer single-use products are employed. In addition, cost saving factors are a major advantage as recycled methods are employed and this matter will be discussed later in this chapter.

Lint generation

Airborne particulates, and specifically lint, can create severe complications during surgical procedures. Nonwoven fabrics such as those made with wood pulp fiber,

© Woodhead Publishing Limited, 2011

among others, have been identified as leading to post-surgical difficulties such as intestinal obstructions due to peritoneal adhesions. Additional postoperative problems included incisional hernias and chronic abscesses at the wound site (Belkin, 2000).

Researchers evaluating a number of materials used in surgical applications reported that some nonwoven fabrics demonstrated very low resistance to abrasion. Some nonwoven cellulose laminate material produced more than 600 times the weight of lint, relative to a woven surgical material, in the same test (Belkin, 2000). The preceding demonstrates the need for selecting surgical materials which have been engineered to produce low levels of lint.

Comfort

The subject of comfort is often based on the perception of the wearer. Utilizing any specific garment type, a selection of wearers, responding to critically planned questionnaires can result in meaningful results, Two, or more apparel items are usually involved for comparative analysis. To the extent that the procedure is time consuming, the method is not always used. There is an opportunity for producers and users of various products to explore research which may offer new information in this field.

Personal protective apparel (PPE) such as fluid impervious surgical gowns are designed to be made with coated and/or laminated materials to prevent fluid penetration. As a guideline, a test evaluating moisture vapor transmission has been used to offer some indication of breathability and comfort (ASTM, E96, 2005). While there is no accepted industry standard for this test, some suppliers of products believe that a performance level of at least 500 g/m^2/24 h, using this test method, offers an indication of wearer comfort.

3.4 Types of reusable textiles used for medical applications

During any given day, hospitals, long-term care facilities and many other healthcare units employ hundreds of different textile materials. Many of these products will be described within the following outline.

3.4.1 Surgical packs

As previously outlined, the concept of using hygienically clean, sterile textile materials originated with the work of Florence Nightingale, among others in the nineteenth century. Utilizing the technology of that era, 100% cotton sheeting fabrics were employed for the first products used in surgery, where a clean and eventually sterile atmosphere was maintained.

© Woodhead Publishing Limited, 2011

New surgical materials for the operating room (O.R.) were developed during the twentieth century and, beginning in the 1960s, until the latter years of the century, many new concepts were developed and introduced. These developments included the characteristics of improved fluid barrier performance. In addition, many of these materials also displayed low lint generation, reduced flammability and increased durability to wear and laundering (Rutala and Weber, 2001). Some of the basic materials utilized, and in many cases developed, for reusable surgical products, are described in the following sections.

Sheeting materials

Muslin (140 count) and percale (180 count), woven sheeting fabrics were originally used for surgical gowns, drapes and wraps. These were 100% cotton initially. During the late 1950s and early 1960s, 50/50 polyester/cotton versions of these materials were developed and introduced.

Largely supplanted by more specialized products, in recent years, which offer fluid resistance, as will be discussed, 50/50 polyester/cotton sheeting materials continue to be used. This may be the case in certain sections of the Third World. The products continue to perform effectively in assisting to maintain a sterile field. Accordingly, where the sheeting products may be used, in some cases because these are the only products available, they offer a benefit to patients (Rutala and Weber, 2001).

Fluid resistant, polyester/cotton materials

Based on an extremely dense woven, plied yarn fabric, with fluoropolymer finishing technology, this 50/50 polyester/cotton material predated the OSHA bloodborne pathogen regulations. Following the promulgation of the OSHA regulations, this methodology has been utilized for surgeon's gowns, in conjunction with surgical drapes and wraps. This combination of products has demonstrated the ability to assist in both meeting the need to promote and maintain a sterile field and to support the requirements of the bloodborne pathogen rule. Fluid resistant performance of the fabric has been shown to test in the 40–60 cm range, based on the AATCC 127 Hydrostatic Head test method.

Fluid resistant, continuous filament polyester

At about the time the Bloodborne Pathogen Rule was promulgated, a high count, fluid resistant multifilament polyester material was introduced for surgical pack products. Based on fine denier continuous filament polyester fibers, these fabrics have been woven even tighter than spun yarn materials. With the addition of a fluoropolymer finish, a high degree of fluid resistance is found, reaching hydrostatic pressure test results in the 60–90 cm range.

© Woodhead Publishing Limited, 2011

Static control polyester materials

Where static control is required, as is the case in most operating rooms, a version of the 100% continuous filament polyester material has been developed and successfully used throughout the world. The fabric construction is similar to the 100% polyester version, but a conductive carbon impregnated polyester yarn is woven into the fabric at spaced intervals, resulting in a 99% polyester/1% conductive carbon blend. As in the case of the 100% polyester product, a durable fluid resistant finish is applied to the static control product.

The conductive version of this technology can be shown to meet the static resistant requirements of NFPA code 99 (NFPA, 2005) for use in surgical suites utilizing flammable anesthetics. In addition, to the extent that the modern O.R. utilizes a great deal of electronic monitoring equipment, static control is important to avoid electrostatic discharge which might under some circumstances interfere with the proper functioning of this instrumentation.

Fluoropolymer reapplication methods

As outlined in the preceding sections, fluoropolymer finishes are applied to polyester/cotton, 100% polyester and polyester/conductive fiber fluid barrier products. Under some circumstances these finishes may be found to lose their fluid resistant efficacy during institutional laundering. A method for reapplication of this finish has been developed and used successfully, as needed.

Some laundry operations opt to apply the fluoropolymer reapplication methodology during every processing of fluid resistant products as an assurance that fluid barrier performance is continually maintained. Other laundries apply the technology on an as-needed basis. Whichever approach is followed, the methodology exists to assure that excellent barrier performance is maintained (Zins, 2006).

Coated and laminated fabrics

A number of products have been engineered to produce materials which can offer fluid penetration resistance levels at the 140–160 cm range, or higher (hydrostatic pressure test) (AATC,127). Referred to previously the hydrostatic head test generally reaches a level of perhaps 90–100 cm. Accordingly, the precise level of fluid resistance, in this particular test, has not been specifically determined for these fluid impermeable materials.

The ASTM F23 Protective Apparel Committee has developed two individual tests to demonstrate fluid impermeability. These are ASTM test method F 1670-07 for Resistance of Materials Used in Protective Clothing to Penetration by Simulated Blood (ASTM F1670, 2007) and ASTM test method F-1671-07 for Resistance of Materials Used in Protective Clothing to Penetration by

© Woodhead Publishing Limited, 2011

Blood-Borne Pathogens Using a Phi-X 174 Bacteriophage Penetration as a Test System (ASTM F1671, 2007). Included among the technologies which have been developed and used for producing fluid impermeable materials in surgical gown and drape applications are the following:

Polytetrafluoroethylene (PTFE) microporous membranes: This technology combines (laminates) a fluid impermeable membrane between two layers of warp knit polyester fabrics. The PTFE membrane offers fluid impermeable characteristics but requires support for institutional use which is afforded with the two layers of knit material mentioned.

Coated fabrics: A number of coated materials have also been found to offer fluid impervious performance. These include both silicone and polyurethane. Generally the coatings are applied to 100% polyester warp knit fabric constructions.

Seam sealing: The sleeves of the surgical gowns need to be sealed to prevent fluid penetration at that point. Heat sealable tape products are applied in this situation. In the case of polyurethane coated products, a methodology has been engineered whereby ultrasonic bonding of the seams offers fluid impermeable performance with that technique (Zins, 2006).

3.4.2 Regulatory controls

Personal protective equipment (PPE) such as surgical and precaution gowns are covered by the OSHA bloodborne pathogen standards (OSHA). In addition to the OSHA regulations, all surgical gowns, wraps and drapes have been classified by the U.S. Food and Drug Administration (FDA) as medical devices. Accordingly, manufacturers of these products must also comply with FDA medical device regulations, which requires the completion of a pre-market notification (510 (K)) filing with the FDA prior to the marketing of a new medical device (FDA, 1977).

ANSI/AAMI PB70-2003

This standard was developed and introduced by the Protective Barriers committee of the Association for the Advancement of Medical Instrumentation (AAMI, 2003). The standard is entitled 'Liquid barrier performance and classification of protective apparel and drapes intended for use in health care facilities'.

The purpose of the ANSI/AAMI document has been defined within the standard narrative as follows:

> Surgical gowns, other protective apparel, surgical drapes and drape accessories are devices intended to promote infection control practices and help protect patients and healthcare workers. The standard is based on key barrier performance tests that are used to classify the subject products into levels of performance. Knowledge of these defined levels of performance will allow informed and consistent choices about the type of protective product necessary for the situation at hand.

© Woodhead Publishing Limited, 2011

Table 3.2 AAMI Standards of Fluid Barrier Performance (Surgical Gowns and Drapes)

Level	Requirements
Level 1	Must show test results (MSTR) equal to, or less than 4.5 g; AATCC 42, 2000
Level 2	MSTR equal to, or less than 1.0 g; AATCC 42, 2000 MSTR equal to, or greater than 20 cm; AATCC 127, 1998
Level 3	MSTR equal to, or less than 1.0 g; AATCC 42, 2000 MSTR equal to, or greater than 50 cm; AATCC 127, 1998
Level 4	Must pass ASTM F 1671, 2003 (bloodborne pathogens; bacteriophage) Must pass ASTM F 1670, 2003 (synthetic blood)

As shown in Table 3.2, there are four classifications of barrier performance outlined in the standard, ranging from Level 1, the minimum level of fluid performance, to Level 4, the highest classification of fluid performance in the standard.

The fluid resistant test methods shown in this standard to determine fluid resistant performance are the following:

AATCC 42 – Impact Penetration (AATCC, 42, 2007)
AATCC 127 – Hydrostatic Pressure (AATCC, 127, 2008)
ASTM F1670, 2007 – Resistance to penetration by synthetic blood (as previously outlined)
ASTM F1671, 2007 – Resistance to penetration to a simulated virus (as previously outlined) (AAMI, 2003).

3.4.3 Precaution apparel

Precaution apparel, also known as precautionary apparel, and in some instances referred to as isolation apparel, represents PPE. In many respects these products are similar to surgical gowns. A major difference is that precaution gowns are not intended to be used in the O.R.

The bloodborne pathogen rule (OSHA), referred to previously, applies to all healthcare workers, including emergency care (ER) workers and healthcare professionals exposed to bloodborne pathogens within their respective medical care duties. The level of exposure must be ascertained by the healthcare facility through an Exposure Determination (OSHA, 1991).

Precaution gowns and/or professional coats can be supplied, made with fluid resistant, 100% continuous filament polyester fabrics. They may also be produced with a 99% continuous filament polyester/1% conductive carbon material where static control is required. Blends of 50/50 polyester/cotton material (also fluid resistant finished) are also used in this application. The fluid resistant technology, as previously described for surgical pack products is a similar methodology utilized for this end use application.

© Woodhead Publishing Limited, 2011

3.4.4 Professional attire

Within hospitals, clinics, long-term care facilities and doctors and dentists offices, healthcare workers require numerous apparel items, in addition to surgical and precaution products (PPE), as previously defined. Included in this listing are long and short lab coats, scrub apparel, various aprons and warm-up jackets. In addition, many hospitals, and other healthcare institutions, offer dresses, shirts and pants to many support personnel functioning within food service, housekeeping, engineering and pharmacy departments, among others.

All of these products (including the surgical items mentioned previously) are expected to be durable to the heavy duty work which most employees encounter in their normal daily routines. In addition, these items must withstand the rigors of institutional laundering, the details of which will be discussed later in this chapter.

Originally, prior to the 1950s, many of these vocational garments were made with 100% cotton materials. Polyester/cotton blends, including those with durable press, soil release and moisture wicking capabilities have become the dominant materials used for many professional attire products used during the latter part of the twentieth century and beyond.

3.4.5 Patient apparel

Patient gowns are issued to all those individuals either spending the night in a healthcare facility for a surgical procedure, tests, or observation. Often, patient gowns are also worn by individuals with appointments as outpatients (not spending the night) at a healthcare unit where surgical procedures or tests are also performed.

Fabrics

Typically made with a light weight (within a 3.5–4.5 ounce/square yard range (130–170 g/m^2)) are 50/50 polyester/cotton fabrics. In some cases, 'cotton rich' blends are used, such as 55/45 cotton/polyester blends. The materials are often printed on white backgrounds. In some cases solid light or medium shades are used for these products.

Characteristics and practices

The gowns are not necessarily considered to be comfortable to patients, partly due to the fact that they do not always promote individual modesty. Pyjamas may, in some situations, be issued, particularly to long-term patients. However, an advantage of patient gowns is that they lend themselves to efficient physical examinations and to tests and bedside procedures, such as medication injections and blood sampling, all of which represent routine treatment and practice.

© Woodhead Publishing Limited, 2011

Flammability requirements

For all patient apparel (as well as all healthcare garments) flammability standards have been issued for some time (CPSC, part 1610). A separate flammability standard has also been established for children's sleepwear (CPSC, parts 1615 and 1616). In some cases in the United States (and possibly elsewhere) other state/local flammability regulations may also be in place for patient apparel.

3.4.6 Sheets and pillowcases

Hygienically clean sheets and pillowcases represent a basic need of every hospital and other healthcare facilities where patients may require overnight or temporary bed care. Typically, sheets and pillowcases used in healthcare facilities are white and have been predominantly blends of 50/50 polyester/cotton for at least three decades. Traditional muslin (T 140) sheeting is used and in some cases, higher count (T 180) percale sheetings may also be used.

100% polyester

A recent innovation has been the development of a 100% polyester bed sheet material for institutional use. Based on a continuous filament polyester woven construction, reports indicate that the product is soft and offers cotton-like hand. The products are also reported to have been engineered for soil release and moisture wicking performance. In addition, the sheets are reported to maintain excellent dimensional stability through continued processing. Further characteristics are reported for the sheets to retain their shade of white through extended use, as well as offering good resistance to staining and tearing (Davis, 2008).

Reports concerning 100% polyester sheets and pillowcases have also indicated some processing problems with institutional folders and ironers. However, equipment modifications such as the addition of static bars to the institutional irons and other processing modifications appear to have alleviated these issues (Davis, 2008).

Knit sheets

An additional development which, in fact, predates the 100% polyester woven product, is a knit sheet which has had the advantage of performing as a fitted sheet for hospitals and other healthcare institutions.

Originally introduced as 100% cotton, a more recent innovation is a 55/45 cotton/polyester blend which offers faster drying for energy savings advantages. The sheets are also manufactured with spandex in critical locations to further promote fittability onto hospital beds.

© Woodhead Publishing Limited, 2011

An additional benefit of the knit product is that these sheets do not generally require processing through a flat work ironer, offering additional energy savings characteristics. The sheets, when fitted onto institutional beds are reported to exhibit minimal wrinkling features.

3.4.7 Surgical toweling

One hundred percent cotton huck toweling, and other cotton products, continue to represent the bulk of surgical toweling products employed and are part of most, if not all, surgical packs. The materials are highly absorbent and remain as a reliable staple for this aspect of O.R. procedures. The promising results reported for 100% polyester sheets and pillow cases has prompted the development of the concept for surgical toweling products. However, for the present, 100% cotton materials remain as the primary product used for this application.

3.4.8 Underpads

In extended care facilities, as well as in hospitals, reusable underpads continue to be required for patient care. Conditions of incontinence represent an ongoing requirement for these products which prevent bodily fluids from penetrating institutional mattresses. In many hospital situations, patients, particularly following surgery, frequently exhibit bodily fluid issues requiring the need for underpads. This need can also be found following infant delivery and in some emergency room treatments. As will be outlined, underpads also contribute to good patient care, particularly for long-term residents.

Basic technology

Reusable underpads can vary in size and components, but the methodology which has been developed and utilized commercially consists of a three layer concept, as follows:

The top layer, upon which the patient lies. This section of the underpad is made with a moisture wicking surface which draws liquids away from the patient and into the middle layer.

The middle portion of the product consists of a highly absorbent polyester/rayon unit, known as a ‘soaker’.

The bottom layer is made with a fluid impermeable coated barrier fabric which prevents liquids from soaking through to the mattress (MIP, Inc.).

The size of underpads can vary. Widths are standardized at 34 inches, the width of a hospital bed and mattress. Lengths can vary from 36 to 45 inches (MIP, Inc.).

© Woodhead Publishing Limited, 2011

Prevention of bed sores

As shown in the preceding, reusable underpads serve the purpose of containing liquids to prevent these from soaking through to mattresses. In addition, the underpad product also serves to assist the healthcare facility staff in preventing patient bed sores.

The use of reusable underpads has been shown to result in a reduction of bed sores (also known as pressure sores or pressure ulcers) for bedridden patients. The products assist in this manner by promoting improved fluid containment and greater patient comfort (ARTA, 2005).

There are a number of specific factors which are responsible for the cause of pressure sores. These include heat, pressure, friction, moisture and shear. All of these determinants must be taken into consideration in treating extended care individuals. Trained personnel can balance the selection of the proper incontinence pads and their replacement, as necessary to manage the five listed threats so that skin breakdown will be minimized. In addition, a properly selected underpad can be used to assist in frequent turning of patients, incapable of turning themselves and this action can also help toward preventing skin breakdown, which can lead to pressure ulcers.

Cost factors

It has been estimated that one bed sore costs between $5000 and $40 000 to heal. Accordingly, the selection of the correct underpad, properly managed, for the care of the patient, represents an important matter in containing rising healthcare expenses (Paradee, 2004).

3.5 Processing procedures

Reusable healthcare textile products require processing which includes such steps as sorting, laundering, drying, and in some cases ironing and/or sterilization. The following details offer certain basic guidelines for these various procedures.

3.5.1 Sorting

Following use, institutional textiles should be sorted (separated) for degree of soil. Light soil items should not be processed with heavily soiled products. Sources of soil might be blood or other body fluids. In some cases greasy soil and/or food soil may also be related to heavy soil. If sorting by soil level is not practiced, difficulties such as soil redeposition may occur. Depending on soil levels and types differing wash formulas may be selected.

Separation of colors also needs to be a procedural principle. White materials should always be processed separately from colors. In a similar manner light shades should not be laundered with dark shades such as navy, dark brown or

© Woodhead Publishing Limited, 2011

black. Color transfer from dark shades to white or light shade products may be experienced if proper color differentiation procedures are not maintained.

3.5.2 Laundering

Institutional laundering has been identified as being dependant upon the factors of temperature, time, chemical action and mechanical action.

Standard laundry processing

A general institutional wash formula consists of the following points:

Time	30–45 minutes
Temperature	160–180°F (71–82°C)
Mechanical action	Based on the rated capacity of the washer
Chemical action	
	pH 11.0–11.5
	Surface active agents
	Bleaches – chlorine

Laundering polyester and high percentage polyester products

For 100% polyester products or for materials containing high percentages of polyester (50% or greater), a potential for alkaline hydrolysis of polyester exists. Accordingly pH should be reduced to the level of 10.5 or lower. Reduced pH levels will also minimize the potential for degradation of fluid barrier finishes, previously applied to fluid resistant materials.

Lower temperature laundering should be used for polyester and/or high percentage polyester products. Temperatures in the 140–160°F range should be employed. Polymers such as polyester may be subject to heat damage, and in some cases, wrinkling difficulties with the use of higher temperatures.

Continuous batch washers

In recent years continuous batch washers (CBWs), also known as tunnel washers, have been used as an alternative method to conventional institutional washing machines. CBWs offer built-in water reuse systems and also offer energy saving capabilities. The method offers high throughput and, in addition, delivers significant increases in automation.

Tunnel washers also require significantly lower water use. Traditional washers utilize 3.0+ gallons of water per pound (25 l/kg) of textiles processed. CBWs, in comparison, require 0.5–0.7 gallon of water per pound (4–6 l/kg), a significant saving in the cost of water and energy.

© Woodhead Publishing Limited, 2011

3.5.3 The drying process

Standard drying procedures

Gas-fired tumble dryers represent the method used to dry most healthcare textile products. Often the drying process is preceded by the use of a centrifugal extractor which can remove excess moisture, following the laundering process. Most commercial gas-fired tumble dryers have the capability to reach high heat levels. Stack temperatures (exhaust temperatures) can operate in the 160–180°F (71–82°C) range, or higher.

Drying polyester-containing products

Many textile products (as previously outlined) are either 100% polyester, or contain high levels of polyester, and these items dry more rapidly than cotton, or blends with high percentages of cotton. Accordingly, drying is effective at lower temperatures. This reality offers energy savings opportunities. On this basis, 150°F (66°C) exhaust temperatures can be used and this temperature should be maintained for 3–5 min, or until the dryer load appears to be dry.

Cool down cycles

A final cool down cycle is normally used, particularly for garments made with polyester materials. A temperature of 100°F (38°C) should be maintained for a sufficient period, allowing the materials to leave the tumble dryer in a dry state. As a guideline, to be certain that the cool down cycle has been appropriately executed, garments should not be hot to the touch, as they are removed from the dryer (Tinker, 2008).

3.5.4 Steam sterilization

Surgical packs are sterilized in a number of methods with steam sterilization representing the most common form utilized to achieve a sterile pack. As previously outlined, a sterile pack is one of the principles used in maintaining a sterile field in the O.R.

Typical steam sterilization conditions

Based on current practices designated by the AORN, there are two methods of steam sterilization techniques followed. These are the dynamic air removal process (vacuum procedure) and the gravity displacement procedure. Current recommended times, and temperatures for vacuum sterilization are 270°F (132°C) for four minutes. For the gravity displacement method, a temperature of 250°F (121°C) for 30 minutes is recommended. Guidelines are also designated for drying times and temperatures, to avoid the possibility of storing wet packs (Spry, 2008).

© Woodhead Publishing Limited, 2011

3.6 Healthcare costs

As this chapter is being written, a major debate is taking place in the United States concerning healthcare reform. An attempt will not be made to explain the many facets of this critical matter. However, one issue is clearly of significant concern and that is the ongoing expense of medical care (Iglehart, 2009). Factors responsible for continually increasing healthcare spending include such realities as an aging population, with 'baby boomers' at, or close to, retirement age, and a general feeling of entitlement that citizens of a wealthy nation expect from government leaders. Other issues include waste, fraud and abuse (Iglehart, 2009).

3.6.1 World healthcare costs

As shown in Table 3.3, healthcare spending of many nations can be compared when studying these expenses as a percent of gross domestic product (GPD). The comparison discloses that the U.S. has spent a higher percent of GPD than many other industrialized nations. This fact is one reason driving the current healthcare reform debate in Washington. However, the figures also disclose that for virtually all nations, spending for healthcare has demonstrated a constant increase since the beginning of the twenty-first century (Health Expenditures, 2010). There is clearly a universal need to control the rising expense which medical care represents to our global society.

3.6.2 Strategies for containing healthcare costs

Managers of healthcare, within government and the private sector, may well ask themselves if there are current practices which might be changed and thereby reduce medical care expenses. As previously outlined, such factors as waste, fraud

Table 3.3 Total health expenditures, as a percent of gross domestic product (GPD), for selected industrialized nations

Country	Year			
	2000	2002	2004	2005
Canada	8.8	9.6	9.8	9.8
France	9.6	10.0	11.0	11.2
Germany	10.3	10.6	10.6	10.7
Japan	7.6	8.0	8.2	8.4
Sweden	8.2	9.0	9.2	9.2
Switzerland	10.3	11.0	11.4	11.4
United Kingdom	7.2	7.6	8.0	8.2
United States	13.2	14.7	15.2	15.2

© Woodhead Publishing Limited, 2011

and abuse have been cited as being among the reasons for rising healthcare costs (Iglehart, 2009). An additional factor for consideration is the estimate by leading analysts that approximately between 70 and 80% of surgical packs are made with single use, disposable materials. This means that only 20–30% of O.R. materials are reusable. There has been an ongoing debate for at least a decade, and probably longer, as to which of these (reusable or disposable) are less costly to a healthcare institution. A review of the matter discloses the following.

Winter Haven Hospital, Winter Haven, Florida

A study at this facility reported the results of an O.R. linen program which converted disposables to reusables with a finding of significant cost savings, and with physicians and staff extremely pleased with the results. On a cost per procedure basis, the reusable products were calculated at $26.45; and relative to the previously used disposable materials, at $37.21. This change signified a nearly 30% decrease in expenses (Branham, 2006).

Mercy Healthcare, Sacramento, California

An annual savings of $60 000 has been reported by this California-based medical facility. These results were based on the conversion to reusable fluid impermeable surgical gowns as well as towels at six units within the organization (ARTA, 2005).

American surgeon report

Additional annual cost savings of $120 000 were reported in a study of surgical textile products where reusable materials replaced disposables (Digiacomo *et al*., 1992).

Cleveland Clinic

A report of the findings at the Cleveland Clinic described a saving of $287 000 annually through the utilization of reusable surgical gowns (Jordan, 1990).

Intermountain Healthcare System, Utah

A $250 000 annual saving was reported by this organization as they converted from disposable to reusable surgical packs (Hall, 1994).

3.6.3 Cost analysis breakdown

As shown in Table 3.4, various cost components have been compared including initial purchase price, laundering, pack making and waste disposal, among

© Woodhead Publishing Limited, 2011

Table 3.4 Cost comparisons (in US$) for reusable and disposable surgical gowns with an estimated initial purchase price of $60.00 per reusable gown and $4.50 per disposable gown

	Reusable	Disposable
Cost per use	1.20*	4.50
Administrative costs	0.15	0.15
Laundering	0.50	0
Pack making, sterilization	0.40	0
Waste disposal	0	0.25
Total cost per use	2.25	4.90

* Based on 50 processings and uses.

others. This format allows a comparison to be made between a reusable and disposable product. The figures shown represent estimates based on discussions with various producers and users within the health care sector. Obviously, depending on products used, cost factors may vary, but it is believed that the relative cost/use figures shown represent a realistic comparison. As shown, the total cost per use for a single use disposable surgical product calculates to be $4.90 relative to $2.65 for a reusable product utilized through 50 use/laundering cycles (ARTA 2005).

There are additional economies realized with reusable textiles. Surgical gowns and drapes are often extended for additional use for alternative applications, once fluid resistant performance may be altered at 50 or more cycles. Products such as surgical gowns can be continually used by food service, housekeeping or laundry workers. In these cases the need for fluid resistance is not a critical factor and workers can use the garments as general cover up purposes, as needed. In a similar manner, surgical wraps and drapes, which may no longer be fluid resistant, can be recycled for such applications as instrument or machinery covers, or, depending on size, for use as tarpaulins, as needed.

A practice which has been accepted and used for many years is the application of heat sealable patches placed over small cuts, or holes, which may develop through extended use. Heat seal patches and equipment for their application are commercially available for the use of healthcare institutions.

3.6.4 The hidden cost of waste

The U.S. EPA has compiled a roster containing many dozens of environmental expense items, many of which are considered to be ‘potentially hidden’ (see Table 3.5). Most of these costs are not usually identified by normal accounting systems, and may not be figured in the total expenses associated with a product or process. Such costs as obtaining regulatory permits, or eventual land remediation demands and related legal expenses, are among these potential ‘hidden costs’. Obviously,

© Woodhead Publishing Limited, 2011

Table 3.5 Hidden environmental costs of products resulting in waste: a partial list

• Reporting	• Remediation
• Monitoring	• Labeling
• Testing	• Pollution control
• Record keeping	• Medical surveillance
• Training	• Waste management

product groups which create waste result in many hidden costs, and are significantly more expensive than generally presumed (DeSimone and Popoff, 2000).

3.7 Future trends

The medical care sector is a dynamic and growing group of interrelated global activities. Many developments, actions and challenges exist and the following are some key directions for current consideration.

3.7.1 Comfort studies

As previously outlined comfort evaluations represent a course of research which can add knowledge and value to the performance characteristics of reusable textiles. Improved comfort, fluid impervious products, particularly for PPE, represents an ongoing need. Bearing in mind that some surgical procedures last several hours or more, the need for highly fluid impervious materials which offer greater breathability presents a major challenge and opportunity.

3.7.2 Improved performance incontinence materials

The technology of underpads to address conditions of patient incontinence has been previously described. There appears to be a development, with reusable underpads, which may offer a number of improved characteristics (Shander *et al*., 2009).

The new methodology offers an increase in the speed of wicking moisture away from the patient's body. In addition, claims are made for a middle layer with higher absorbency characteristics. Furthermore, the development reports a moisture barrier layer which not only is fluid impermeable, but is engineered to maintain the pad more securely in place with fewer tendencies to bunch up under the patient.

All of the preceding features are reported to combine performance features leading to dryer, more comfortable long-term care patients, less likely to experience skin breakdown conditions (Shander *et al*., 2009).

© Woodhead Publishing Limited, 2011

3.7.3 Antimicrobial technology

With the ongoing challenges of infectious disease, interest has urged the development of numerous antimicrobial (A/M) products for reusable healthcare textiles. Among these A/M technologies are the following:

N-halamine-based finishes (Williams *et al*., 2006)
Bioactive materials (Edwards *et al*., 2006)
Antimicrobial acrylic fiber (Lee *et al*., 2006)
Copper impregnated antimicrobial textiles (Borkow, 2008)
Organic functional silane antimicrobial technology (Clarke *et al*., 2006).

The previous listing of A/M products represents a broad overview of several methods available for possible investigation. The grouping is not an exhaustive overview of the subject, but represents a number of directions which organizations may wish to study for possible future applications.

Government regulations

It should be noted that in the United States A/M methods are broadly covered by EPA regulations under the Federal Insecticide, Fungicide and Rodenticide Act (EPA, FIFRA, 2008). Similar regulations may be overseen by comparable regulatory agencies, around the world. Accordingly, as this product type may be investigated, an understanding of the appropriate regulatory requirements should be reached.

3.7.4 The Healthcare Laundry Accreditation Council (HLAC 2010)

The Healthcare Laundry Accreditation Council (HLAC) is a relatively new concept which offers a promising new dimension to the reusable healthcare textile sector. Introduced during recent years, the HLAC is a non-profit organization formed for the purpose of inspecting and accrediting laundries processing healthcare textiles for hospitals, nursing homes and other healthcare facilities.

The mission of HLAC is to publish high standards for processing healthcare textiles in laundries, and to provide a voluntary inspection and accreditation procedure that recognizes those laundries that meet these high standards (Reino, 2008). An HLAC accredited laundry has proven itself as a premier company with which healthcare institutions can partner. HLAC accreditation demonstrates that the laundry is performing at a high level of operational efficiency and excellence and those employees have been trained to productively deliver a consistent flow of hygienically clean healthcare textiles.

Laundries, having been HLAC accredited are in an enhanced position to assist healthcare facilities in meeting the challenges of bloodborne pathogen containment,

© Woodhead Publishing Limited, 2011

infection control efforts and the overall goal of promoting the highest level of patient care and satisfaction possible (HLAC, 2010).

3.7.5 Guide for the use of environmental marketing claims

The U.S. Federal Trade Commission (FTC) has solicited comments as part of its review of current rules and guides. Specifically, the FTC is reviewing guides for the use of environmental marketing claims, also known as green guides (Clark, 2007). While rules and regulations have not been established at this time, it would appear likely that some statutes will be issued at some point in the future.

To the extent that environmental marketing claims are being stated by producers of both reusable and disposable materials, the entire industry should be appraised of this potential regulatory matter. The FTC has raised many points concerning this matter. In one response (Zins, 2008) reference was made to the Bruntland Commission of United Nations and its definition of sustainable development. That definition emphasizes that 'sustainable development is that which meets the needs of the present without compromising the needs of future generations' (Meadows, 2007). The FTC is urged that, among many factors, the Bruntland Commission definition should serve as a major principle, as the matter continues to move forward.

3.8 Conclusions

This chapter has traced the origins of the sterile field and the discussion of textile materials to supply that need, as well as current challenges in mankind's battle to contain disease. Additional critical factors such as regulatory demands, environmental issues and the search to control rising healthcare costs have also been discussed. An attempt has been made to show how reusable medical textiles support all of these issues as well as the necessity to attain sustainable development in the twenty-first century.

3.9 References

American Association for Textile Chemists and Colorists, standard test method 42-2007, 2007. Technical Manual, Water resistance: Impact penetration test. AATCC, Research Triangle Park (NC).

American Association for Textile Chemists and Colorists, standard test method 127-2008, 2008. Technical Manual, Water resistance: Hydrostatic pressure test. AATCC, Research Triangle Park (NC).

American Reusable Textile Association (2005), Reusable textiles – Performance, cost, environment – The responsible solution. ARTA, Mission (KS).

Association for the Advancement of Medical Instrumentation (2003), Liquid barrier performance and classification of protective apparel and drapes intended for use in healthcare facilities. American National Standard – ANSI/AAMI PB70: 2003. AAMI, Arlington (VA).

© Woodhead Publishing Limited, 2011

ASTM Standard E96/E96M-05, 2005. Standard test method for water vapor transmission of materials. ASTM International, West Conshohocken (PA).

ASTM standard F1670-07, 2007. Standard test method for resistance of materials used in protective clothing to penetration by synthetic blood. ASTM International, West Conshohocken (PA).

ASTM standard F1671-07, 2007. Standard test method for resistance of materials used in protective clothing to penetration by blood-borne pathogens using phi-X174 bacteriophage penetration as a test system. ASTM International, West Conshohocken (PA).

Belkin N L (2000), The role of surgical gowns, drapes and masks in the generation of airborne particulates, *AORN J*, 72(4), 678–680.

Borkow G (2008), Medical applications of copper impregnated antimicrobial textiles, Clemson University Medical Materials and Technology Conference, 26–27 March 2008, Greenville (SC).

Bostridge M (2008), *Florence Nightingale – The making of an icon*. Farrar, Strauss and Giroux, New York.

Branham J (2006), The journey to a reusable OR program at Winter Haven Hospital. The Insiders' Guide to Processing and Marketing Reusable Medical Textiles, Conference, 26–27 April 2006, Indianapolis, IN

Clark D S (2007), Guide for the use of environmental marketing claims, Federal Trade Commission, 16 CFR Part 260, Federal Register, 72(227), pp. 66091–66093.

Clarke D R, White W C and Monticellow R A (2006), An organofunctional silane microbe technology: A broad spectrum non-leaching antimicrobial for protection of medical goods and facilities, Clemson University Medical Textiles Conference, 21–22 March 2006, Greenville (SC).

Consumer Product Safety Commission (CPSC), Part 1610, Standard for the Flammability of Clothing Textiles, Commercial Standard (CS) 191–153.

Consumer Product Safety Commission (CPSC), 16 CFR, Standard for the Flammability of Children's sleepwear, Parts 1615 and 1616.

Davis R (2008), Bed linen breakthrough – 100% polyester, *Textile Rental*, 92(3), 72–74.

DeSimone L D and Popoff F (2000), *Eco-efficiency: The business link to sustainable developmen*t. The MIT Press, Cambridge (MA).

Digicomo J C, Odom J W, Ritota P C and Swan K G (1992), Cost containment in the operating room: Use of reusable vs. disposable clothing, *Am Surg*, 58(10), 654–656.

Edwards J V and Goheen S C (2006), Performance of bioactive molecules on cotton and other textiles, *Res J Text Apparel*, 10(4), 19–32.

EPA, CFR Part 60 (1995), Standards of performance for new stationary sources and emission guidelines for existing sources; Medical waste incinerators, proposed standards and guidelines, and notice of public hearings, 27 February 1995.

EPA, CFR Part 60 (1997), Standards of performance for new stationary sources and emission guidelines for existing sources: Hospital/medical/infectious waste incinerators: Final rule, 15 September 1997.

EPA (2008), Federal Insecticide, Fungicide and Rodenticide Act, as amended through P.L. 110–246, effective 22 May 2008.

FDA, 21 CFR 807 (1977), Establishment, regulation and device listing for manufacturers of devices, premarket notification: 510(k), final rule, 23 August 1977.

Goldberg M S *et al*. (1995), Low birth weight and preterm births among infants born to women living near a municipal solid waste landfill site in Montreal, Quebec, *Environ Res*, 69(1), 37–50.

© Woodhead Publishing Limited, 2011

Goldberg M S *et al*. (1999), Risks of developing cancer to living near a municipal solid waste landfill site in Montreal Canada, *Arch Environ Health*, 54(4), 291–296.
Grady S M and Tabak J (2006), Biohazards: Humanity's battle with infectious disease, Facts on File, Inc., An Imprint of Info Base Publishers, New York.
Hall J (1994), Linen firms vie for OR business, *Hosp Purchas News*, 15 May, p. 1.
Harding A S (2000), Antibiotics and bypass surgery, in *Milestones in Health and Medicine*. Oryx Press, Phoenix (AZ), pp. 19, 48,146, 232.
Hogan M A, Bowles D and White J E (2003), *Nursing Fundamentals: Reviews & Rationales*. Prentice Hall, Upper Saddle River (NJ).
Hood E (2003), Toward a new understanding of aging, *Environ Health Perspect*, 111(14), A756–A759.
Hospital Laundry Accreditation Council. HLAC Fact Sheets. Available: www.hlacnet.org (accessed 28 February 2010).
Iglehart J K (2009), Finding money for healthcare reform – Rooting out waste, fraud and abuse, *N Engl J Med*, 361(3), 229–231.
Jordan J (1990), Cleveland Clinic study projects huge savings following conversion to reusable surgical gowns, Laundry News, December, 1990, p. 10.
Landrigan P, Garg A and Droler D B J (2003), Assessing the effects of endocrine disruptors in the National Children's study, *Environ Health Perspect*, 111(13), 1678–1682.
Lee J, Broughton R M, Liang J, Worley S D and Huang G S (2006), Antimicrobial acrylic fiber, *Res J Text Apparel*, 10(4), 61–66.
Lesch J E (2007), *The First Miracle Drugs*. Oxford University Press, New York.
Levy E and Fischetti M (2003) *The New Killer Diseases*. Crown Publishers, New York, p. 55.
Lord J T (American Hospital Association), Sanders W H and Ulrich D A (U.S. Environmental Protection Agency) (1998), Memorandum of Understanding between the American Hospital Association and the U.S. Environmental Protection Agency, 24 June 1998.
McGrath K A (ed.) (1999), *World of Biology*. The Gale Group, Farmington Hills (MI), p. 332.
Meadows D (2007), ASTM standard breaks barriers to global sustainable development, ASTM International, Conshohocken (PA).
MIP Inc., Underpads, Available: www.mipinc.com (accessed 22 February 2010).
National Fire Protection Association (2005), NFPA 99: Standard for healthcare facilities, 2005 edition. NFPA, Quincy (MA), pp. 635–636.
OSHA, 29 CFR Part 1910.1030, Occupational exposure to bloodborne pathogens; Final rule, 6 December 1991.
Palmer S R *et al*. (2005), Risk of congenital abnormalities after the opening of landfill sites, *Environ Health Perspect*, 13(10), 1362–1365.
Paradee K (2004), Reusable incontinence products: A good start, Clemson University Medical Textile Conference, 24–25 March 2004, Greenville (SC).
Practice Greenhealth, Available: www.practicegreenhealth.org (accessed 23 June 2011).
Reino J (2008), Healthcare Laundry Accreditation Council, (HLAC), ARTA, The Insiders' Guide II, Reusable Medical Textiles: The role of textiles and successful packroom operations Conference, 30 April to 1 May 2008 Durham (NC).
Rutala W A and Weber D J (2001), A review of single-use and reusable gowns and drapes in health care, *Infect Control Hosp Epidemiol*, 22(4), 248–257.
Schmidt R (2000). *Simplified Life Cycle Assessment of Surgical Gowns*, (second draft), dk-Teknik Energy & Environment, Soeborg, Denmark.

© Woodhead Publishing Limited, 2011

Shander K, Stamas C and Larson J C (2009), 'Protecting what matters', White Paper (September), Encompass Group, LLC, McDonough, GA.

Spry C (2008), Understanding current steam sterilization recommendations and guidelines, *AORN J*, 88(4), 537–550.

Tinker S J (2008), Surgical textiles-laundering: Balancing quality requirements and productivity needs, The Insiders' Guide II, Reusable Medical Textiles and Successful Packroom Operations Conference. 30 April to 1 May 2008, Durham (NC).

U.S. Census Bureau, Statistical Abstract of the United States: 2009 (128th edition) Washington, DC 2008, p. 222.

Vrijhheide M (2000), Health effects of residence near waste landfill sites: A review of epidemiologic literature, *Environ Health Perspect*, 108(S1), 101–112.

Williams J F, Suess J C, Cooper M M, Santiago J I, Chen T X, *et al.* (2006), Antimicrobial functionality of healthcare textiles: Current needs, options and characterizaion of N halamide based finishes, *Res J Text Apparel*, 10(4), 1–12.

World Health Organization (WHO) (2006), The World Health Report: *Working Together For Health*, WHO, Geneva, Switzerland, pp. 1–5.

Zimmer C (2009), Fairview Medical Center, life cycle assessment: Disposable vs. reusable gowns, Presentation at the meeting of the American Reusable Textile Association board of directors, 29 October 2009, St. Paul, MN.

Zins H M (2006), Environment, cost and product issues related to reusable healthcare textiles, *Res J Text Apparel*, 10(4), 73–80.

Zins H M (2008), Letter to Donald S. Clark, Concerning green guides regulatory review, 7 May 2008.

© Woodhead Publishing Limited, 2011

4

Nonwoven materials and technologies for medical applications

J. R. AJMERI and C. JOSHI AJMERI, Sarvajanik College of Engineering and Technology, India

Abstract: Nonwoven materials (NMs) for medical applications offer numerous advantages both with regard to user requirements and material properties. They guarantee the safety of patients and medical staff because of their superior levels of infection control, sterility and efficiency. Shorter production cycles, higher flexibility and versatility and lower production costs are some of the reasons for the popularity of NMs in medical applications. During the past several years, drylaid, meltblowing, spunbonding, hydroentangling, airlaying and carding, thermal bonding, needlepunching have become important technologies for the formation of NMs for medical applications. The present chapter discusses the key issues, main types and technologies, strengths and limitations of NMs for medical applications and the entire product range covering wound care products, medical gauze, wadding, surgical gowns, surgical caps, surgical masks, drapes and cover cloths, clothing, incontinence products, feminine hygiene products, diapers, wipes, etc. Future innovations, such as accelerators, are also discussed.

Key words: nonwoven materials, spunbond nonwoven, meltblown nonwoven, spunlaced nonwoven, composites, disposable absorbent products, wound care products, surgical products, incontinence care, feminine hygiene, diaper.

4.1 Introduction

Nonwoven materials (NMs) are extensively used in the medical field and in protection against biological agents in other sectors. NMs for medical applications stand out for the numerous advantages they offer, both with regard to user requirements and material properties. For example, they can be designed to deliver critical safety properties, such as protection against infections and diseases. With today's multi-drug resistant strains of bacteria and viruses, NMs can help in the fight against cross-contamination and the spread of infection in a medical or surgical environment. Because they are used only once and incinerated after use, the need for handling is avoided and the spread of contaminants is minimised. Shorter production cycles, higher flexibility and versatility and lower production costs are some of the reasons for the popularity of NMs in medical applications.[1]

During the past several years, drylaid, meltblowing, spunbonding, hydroentangling, airlaying and carding, thermal bonding, needlepunching have been important technologies for the formation of NMs for medical applications.

© Woodhead Publishing Limited, 2011

Most nonwoven products used outside the body are disposable, single-use articles that have the advantage of not requiring sterilisation or cleaning for reuse. However, there are some that can be reused to provide the required function over a limited period of time. In medical applications there are two main functions: first, to absorb the liquid released from the body or the infected area; and second, to help the infected or bleeding area by pressing into it.[2]

NMs are also increasingly a major component in the design of 'smart' wound care products, providing functions such as the creation of a moist wound healing environment, with controlled vapour transmission, absorbency and low skin adhesion.

Most recent nonwoven innovations include the design of new scaffolds for three-dimensional (3D) biological tissue engineering, implantable fabrics that can reinforce natural tissues, and nanofibre nonwoven filtration media offering enhanced particle capture properties. New NMs with improved finishes including liquid repellent, virus proof and bacterial barrier properties have also been developed for applications such as surgical masks, gowns and drapes, especially in view of the high demands of the new European Standards, EN 13795.

The nonwoven business continues to be driven by the hygiene and wipes markets especially in mature markets such as the US, Europe and Japan. In developing markets such as India, Russia, China or Brazil this market is regarded as an opportunity, since demographic growth is an important factor for the development of the local market.[3] Along with increasing personal incomes, the consumption of disposables, such as medical and hygiene products, will definitely increase. In future, product innovations, particularly in areas of composites where different materials processed with different technologies are combined, will be the accelerators.

The present chapter highlights the key issues, main types and technologies, strengths and limitations of NMs for medical applications and the entire product range covering wound care products, medical gauze, wadding, surgical gowns, surgical caps, surgical masks, drapes and cover cloths, clothing, incontinence products, feminine hygiene products, diapers, wipes, etc.

4.2 Key issues of nonwovens

Key issues of NMs are: constituent fibre, assembly structure, the web properties from the nature of the fibre, type of bonding: the chemical or mechanical means of conveying integrity to the fibrous web, finish: chemical and/or mechanical treatments conveyed to the formed and bonded web; each of these issues can have an effect on the absorbency of the resulting structure.

4.2.1 Fibre

Virtually every fibre, both natural and manufactured, has been used in absorbent nonwoven structures. Being the structural element, fibres making up a nonwoven

© Woodhead Publishing Limited, 2011

have a major influence on the absorbency characteristics. The major fibre properties exerting such an influence include the following: polymer type, linear density or denier, fibre cross-section shape, crimp, fibre finish and fine structure. The polymer type, particularly whether hydrophilic or hydrophobic, influences the inherent absorbency properties of the resulting structure. Fibre linear density or denier, related to the cross-section area, influences void volume, capillary dimensions and the total number of capillaries per unit mass.

4.2.2 Web assemblage

The manner in which the fibres are assembled into a web has a profound effect on the web properties. The fibre configuration will have an effect on packing, pore size, capillary dimensions, capillary orientation, etc.; the absorbency properties of the nonwoven structure can also be expected to be sensitive to the nature of fibre arrangement in the web. Web formation can also be supplemented by localised rearrangement of fibres rendering bundling of fibres which enhance the fabric wicking capabilities.

4.2.3 Fibre bonding

A bonding means is required in a nonwoven web to impart mechanical integrity. The bonding can be characterised as derived from either a chemical basis or a mechanical or physical basis; in some cases, it is a combination of the two systems.

Many nonwovens are bonded by the addition of an external chemical binder. The nature of the latter and in particular, the method of application of the chemical to the fibrous web has a profound effect on the absorbency of the resultant structure. Because most binder materials are hydrophobic, the net effect usually is some reduction in absorbency. In mechanical bonding, the inherent characteristics of the fibres are usually unaffected; consequently the effect of mechanical bonding on absorbency of fibres is minimal. However, since mechanical bonding, e.g. needle felting, causes entanglement of fibres, two effects can take place: (i) the entanglement may restrict the inherent ability of structure to swell, and (ii) the fabric may become more resilient and resist collapse when subjected to external pressure. These changes in the behaviour of a web with mechanical bonding can have a significant impact on the capillary absorption of fluid.

4.2.4 Web finishing

In nonwoven processes, a web is generally ‘finished’ as soon as the fibres are assembled into an appropriate structure and bonded by the selected chemical or physical means. A chemical finish may enhance the absorbency of the nonwoven structure, by modifying the wetting performance of a fibre surface, and therefore, affecting the wicking behaviour.

© Woodhead Publishing Limited, 2011

Mechanical softening treatments may involve fibre displacement, web buckling and affect the absorbency of the resulting structure. Embossing, calendering and surface glazing, and other mechanical treatments can be utilised to modify web properties and the related absorbency characteristics. Fibre crimp can influence packing efficiency of fibres and the resulting fabric bulk, both of which can influence the absorbency of a nonwoven structure.[4]

4.2.5 Fibre finish

Fibre finish is used to enhance fibres processing performance in the mechanical equipment used to open, blend and convert the fibre into a web. Because the finish is on the fibre surface, and the latter is often the only segment of fibre encountered by liquid, the finish can profoundly affect wetting, liquid wicking and other properties, directly influencing absorbency. Further morphological features, such as surface rugosity, core uniformity, etc., can somewhat influence absorbency performance. Apart from above issues method of disposal of clinical waste i.e. landfills against incineration, is also crucial.[5]

4.2.6 Performance requirements

The principal design features of nonwovens for medical applications are barrier properties, strength, sterilisation stability, air and vapour permeability or breathability and comfort. The performance requirements of nonwovens for highly specialised medical applications are often complex and require the optimisation of a number of different fabric properties such as:

Tensile properties: often need to be optimised, strengthened when used as surgical gowns where tensile forces are exerted due to body movement, and reduced in orthopaedic bandages to facilitate ripping.

Fabric air permeability: affects comfort, which is of particular importance in wound dressings, where high air exchange prevents overheating, limits bacterial growth and aids in the healing process.

Fabric flexibility: also affects comfort, and permits easy moulding to the shape of limbs in wound dressings or orthopaedic bandages and over the body in surgical drapes.

Liquid interaction properties such as absorbency (or repellency), wicking and strike-through are important in many end uses.

In wound care applications, *high absorbency* is desired which ensures comfort and must provide a barrier to bacterial infection.[6,7]

Absorbent consumer products are designed to hold a specific quantity of absorbed fluid, using a minimum of absorbent, and with design features to provide the required combination of capacity, rate of absorption, comfort and aesthetics. This is true of diapers, sanitary protection products, underpads and other absorbent products.

© Woodhead Publishing Limited, 2011

The most effective products need to provide these features: a special and stable zone for superabsorbent action, fixing this zone physically, mechanisms for immediate acceptance of exudates, means to prevent squeeze out, reduction of strikeback when reducing absorbent bulk, maintenance of product integrity during packaging, shipping, and consumer application.

The basic model for the absorbent core of disposable absorbent products consist of fluid acquisition, distribution and retention components. 'Acquisition' components allow the fluid to enter the absorbent structure quickly. This minimises leakage since the fluid is entrapped into the structure and will not remain as a puddle on the top for very long. If the fluid puddles, any movement of the user that can cause a gap between body and the product will be the potential for leakage. Due to the use of superabsorbent, without a fluid acquisition system, separate or integral to the core, the absorbent core structure would not function at its desirable level.

This issue of absorbent layer has been addressed by two different approaches. The first one, commercialised by Procter & Gamble, provides the target area of lower density web to perform this function. The second commercial approach, by both Procter & Gamble and Kimberly-Clark, was the introduction of layers of different material on the top of absorbent core to perform the acquisition function. Procter & Gamble used their cross-linked cellulose fibre to maintain high porosity of the fluid acquisition zone in dry as well as in the wet stage of the product.

One other variation of the absorbent layer is commonly known as 'surge layer' which is normally composed of long staple fibres which provide efficient wicking channels to fulfill the goal of providing maximum comfort for the end-users by improving the absorbent capacity, e.g. a Dry Web® acquisition or surge layer through air bonded nonwoven.[8]

The second functional component is the distribution layer. An approach to accomplish the rapid fluid distribution function is either to make the structure more dense to provide small pore sizes thus increasing capillary pressure, or to include the reduced pore sizes in the fibres themselves, or both. The most important material that provides the functional characteristic of retention layer in the majority of the cases is the superabsorbent.

The overall trend of NMs for medical applications is thinness. Thinness results in overall comfort improvement but it also creates some problem in quality and protection. The superabsorbent polymer (SAP) particles usually have a sand-like feature, which is not comfortable when it rubs against skin. Also, its gel-like behaviour when wet does not produce a desirable feeling if it comes into contact with the skin. A very thin absorbent product does not always maintain the contact of fluid proximity and thus occasionally creates leakage problems. Application of a superabsorbent fibre (SAF) that has recently been marketed in place of SAP particles may alleviate some of the problems, such as sand-like abrasion to the skin or gel blocking.

The main issue in the design and use of operating room fabrics used to be protection of the patient from contamination by the environment and by healthcare

© Woodhead Publishing Limited, 2011

workers as well as the preservation of sterility of the instruments used in invasive procedures.

Wound care management is an extremely complex medical operation and no single dressing can provide for all eventualities. The successful wound dressing must satisfy several criteria:

- Seal the wound and prevent introduction of external stresses and loss of energy
- Remove excess exudates and toxic components
- Maintain a high humidity at the wound–dressing interface
- Provide thermal insulation
- Act as a barrier to microorganisms
- Be free from particulates and toxic wound contaminants
- Be removable without causing trauma at dressing changes.[9]

In hygiene, medical and wipes applications nonwoven absorbency is the most significant property.[10]

4.3 Main types of nonwovens and technologies for medical applications

During the past several years, drylaid, meltblowing, spunbonding, hydroentangling, airlaying and carding, thermal bonding, needlepunching have been important technologies for the formation of NMs for medical applications.[11,12] Spunbonded (SB) fabric remains the major technology for this end use, comprising almost half of the fabric consumed by the medical/surgical market.[13]

4.3.1 Spunlaced nonwovens

Mechanical bonding, the oldest technique for consolidating fibres in a web, entangles the fibres to give strength to the web. The two most widely used methods are needlepunching and spunlacing, also known as hydroentanglement. Spunlace is one of the most effective bonding processes for nonwovens, as it does not affect any of the properties of the raw materials involved.[14] It uses high-speed jets of water to strike a web to intermingle the fibres. For spunlacing, there are two main technology suppliers on the market: Germany-based Fleissner GmbH, a daughter company of Germany-based Trützschler GmbH & Co. KG; and France-based Rieter Perfojet, a subsidiary of Switzerland-based Rieter Textile Systems.

Spunlaced products are enjoying increasing interest around the world.[15] There is growing demand for lightweight hydroentangled products for medical and hygiene applications especially in Asia, where the Chinese market plays a major role.[16] It is said to offer high fabric properties with regard to bulk, softness, drape and tensile strength.[17,18]

Spunlacing is also gaining popularity in producing disposable products and garments for the operating room. Products made from spunlaced nonwovens include wipes, surgeon's gowns, gauze, disposable protective clothing, plasters,

© Woodhead Publishing Limited, 2011

sponges and bandages.[19–21] Disposable hot-water soluble PVA spunlaced fabrics for surgical scrub suits, gowns and drapes have also been developed.[22]

Improvements in spunlace technology have included machines equipped with lower pressure jets, to save energy, and machines incorporating wood pulp, to allow a more uniform transfer of energy across the total width of the web. With these improvements wipes started their road to success virtually around the world. There is a trend toward lightweight nonwovens in the range of 25–50 g/m^2. This tendency is due mostly to the constant evolution of the manufacturing lines. Line widths range between 360 and 450 cm for wipes, and between 180 and 260 cm for cotton products such as wipes or pads.

Spunlaced materials also typically do not use binders or chemical additives, allowing sterilisation of the fabric at high temperatures.[23] The wipes produced by spunlacing are guaranteed lint free, because it is argued that if a fibre is loose it will be washed away by the jetting process. Procter & Gamble has already converted its baby wipes from airlaid to spunlace.[24] Aqualace spunlace fabrics can be used for the top sheet for feminine hygiene products and as carrier for the back sheets. The main reason for the wide use of these fabrics in medical applications is based on their relatively high absorption abilities.

Modern equipment allows the manufacture of high-quality NMs with a high number of fibres and a low superficial density for the top and distributive layers in children's diapers and female hygiene products, and also as a basis for the back sheet layer.[25] A problem in spunlacing is always water consumption. Fleissner estimates that the average water consumption is 100 m^3/h for an average wipes production line, and some 150 m^3/h for perforated products. Water reclaim in the whole circuit is at 96% without backwashing; and with backwashing, only 1% of the water is lost.

4.3.2 Spunlaid nonwovens

Spunlaid nonwovens are generally appreciated for their good uniformity and mechanical properties at low and even very low basic weights are the first choice for sanitary products. Spunlaid nonwovens are today usually calendered. However, bonding via a calender has well-known drawbacks, such as lack of bulk and softness, degradation of filaments at the melted bonding points, and loss of permeability due to the filmed and impervious area at the bonding points.[26] It is sometimes desirable to combine the spunlaid webs with wood pulp layers to create strong and absorbent wipes. Inline machine configurations cover the two and three layer product structure. Hydroentanglement is also the preferred bonding process in this case to achieve high mechanical properties together with bulk and softness.

4.3.3 Spunbond (SB) and meltblown (MB) nonwovens

Since they came into existence, SB and MB technologies have always been associated with one particular application: hygiene. Due to a steady market growth

© Woodhead Publishing Limited, 2011

and further development of disposable products for baby care, feminine hygiene and medicine, the market share of SB and MB fabrics has constantly been increased. Hygiene is and will remain the most important market for SB and MB technologies.[27] The spunbonding process is a nonwoven manufacturing technique, whereby polymers are directly converted into endless filaments and stochastically deposited to form a nonwoven material.[28]

The use of SB fabrics in coverstock for diapers and incontinence devices has grown dramatically.[29] This is mainly because of the structural characteristics of SBs, which helps keep the skin of the user dry and comfortable. Bicomponent SB fabrics used as inner coverstock have a smooth surface that is soft to the touch and ideal for skin contact. It is readily convertible. SBs are widely used in sanitary napkins and to a limited extent in tampons. The best-selling product on the sanitary products market is the white, 13 g/m^2 nonwoven used in the diaper industry.[30] SB technology gives CD strength and adjustable breathability, resistance to fluid penetration, lint-free structure, sterilisability and impermeability to bacteria for a cost effective solution that is in compliance with the standard requirements of the market and ease of converting.[31,32] In the hygiene sector and thanks to fabric weights of less than 20 g/m^2 SB surpasses carding. And in recent years SB fabrics have been sold at lower and lower basic weights, declining from 17 g/m^2 to 15 g/m^2, and today going down to 13 g/m^2 for a top sheet fabric, for example.[33]

Base material for wound dressings is one of the main application areas of SB nonwovens, which are preferred on account of their textile properties and relatively high abrasion resistance. They can be equipped with high transverse stretch properties, thus allowing freedom of body movement. Recently, spunlaced nonwovens are used in this area due to their advantage of softness and adaptability (high stretch with minimum force).

Very important end-uses of MBs include sanitary applications such as hygiene and incontinence products for babies, adults and feminine hygiene[34,35] and also in disposable gown and drape market and sterilisation wrap segment.[36]

4.3.4 Airlaid nonwovens

Airlaid fabrics are claimed to have higher absorption and faster liquid transfer (acquisition and distribution) compared to the other conventional nonwoven fabrics. The main markets for airlaid products are absorbent core material for feminine hygiene, health care and incontinence products to improve the performance and allow a thinner product to be manufactured.[37–40]

Airlaid products are being used in the production of a new category of the baby diaper product—the swim diaper. The use of airlaid in the swim diaper has opened the avenue toward training pants. From there, the next step for airlaid is into small size diapers and beyond.[41] In the hygiene segment, airlaid allows the pore size of the material to be controlled. Smaller sizes result in better distribution, better

© Woodhead Publishing Limited, 2011

re-wet properties and better suitability for core layers. Larger pore sizes give quick and high absorption but less distribution and are recommended for acquisition layers.[42]

4.3.5 Thermal bonded nonwovens

The process involves the application of heat and pressure on the fibre web to produce nonwoven fabric using calender rollers consisting of a heated male embossed metal roll and a smooth surface metal roll.[43]

Thermal bonded nonwoven and hot air bonded nonwovens are used for producing top layers, bottom layers, sub-layers and acquisition distribution layers (ADL) of diapers, sanitary napkins, panty liners, breast pads, wet wipes and surgical apparels. The thermal bonded nonwoven fabrics are used extensively in manufacturing disposable hygienic products. Thermal bonded nonwoven fabric is made of polypropylene fibre (PP), rayon and bi-component PE/PP fibres. For example PP coverstock found in sanitary and incontinence products of 10-30 g/m^2, based on calender point bonded dry-laid or SB webs, the former using bicomponent fibres.[44] Other disposables include wipes produced from airlaid short fibres, which are through-air bonded to make products in the 25–150 g/m^2 weight range and through-air bonded carded wipe products of about 100–250 g/m^2. Calender bonding is utilised to bond SB, MB and composites to these webs for numerous medical and hygiene applications including surgical gowns and drapes.[45,46]

4.3.6 Composites

Attractive composites can be made with airlaid/spunlace combination. For example, infusion of pulp by airlaying into web during spunlacing enables a fabric to be produced that has comparable absorbency to that obtained using staple rayon but at a lower cost. A typical blend for pulp and fibre is 50/50. A good example of an application where airlaid pulp is fused with spunlace line is baby wipe. Composites of airlaid and spunlaced reduced energy consumption per kilogram of raw material used, the reduction of material loss, the reduction of water consumption through the use of optimised filter systems as well as reliability and minimum maintenance requirements of the lines are decisive factors for the use of spunlace with airlaid products.[47,48]

The most popular combination structure is spunbond–meltblown–spunbond (SMS) or spunbond–meltblown–meltblown–spunbond (SMMS), spunbond–spunbond–meltblown–meltblown–spunbond (SSMMS) in weight ranges from 10 to 25 g/m^2 comprising 1–5 g/m^2 MB microfibres. The production and properties of these are particularly enhanced by the use of bicomponent PP/polyethylene (PE) materials in the preparation of MB webs. SMS structure is generally said to be mechanical barrier because MB is a microporous structure and breathable at

© Woodhead Publishing Limited, 2011

the same time.[49] SMS products of weights from 10 to 70 g/m^2 possess the highest level of protection, and their softness and comfort have been improved considerably.[50,51]

The SB fabric, or SB combined with ultra-lightweight MB fabric, is suited for coverstock for diapers and sanitary products. Commercial SB lines are providing PP/PE bicomponent material for diaper top sheet and it is noted that the trend to fine denier PP SB is continuing with denier lying in the 1.0–1.2 range for diaper use. The SB layers provide high tensile strength in both the machine and the cross-direction whereas the MB microfibres greatly improve visual uniformity and liquid barrier properties. The topsheet given proper hydrophilic treatment combines high strike-through with effective retention of SAP smaller than 100 microns. By adding the airlaid nonwoven processes to the SB technologies even more sophisticated products can be realised: the integration of acquisition layer with topsheet; the integration of diaper core with an acquisition layer or creating monolayer or SB + bicomponent technology.[52]

Other lines are now available that are capable of handling SB, SS, SSS, SMS and SMMS, etc., structure of PP and other synthetic polymers, in speed, exceeding 500 m/min and filament denier lying in the 0.7–10 range. From SMS to SSMMMSS, everything can be manufactured and implemented to produce hygiene products such as baby diapers and medical products such as protective masks and general use such as barrier layer.

Cotton core nonwovens (CCNs)

Cotton core nonwovens (CCNs) are thermally bonded laminates with cotton cores and outer layers of MB PP and/or SB PP webs. The outer MB and SB layers are engineered to effectively transport liquid into the highly absorbent cotton core from the surface. The dry surfaces and absorbent core makes CCNs highly suitable for products such as diaper components (acquisition, core, back sheet), feminine hygiene pads, wipes for baby, surgical packs (barrier gown, drape), sponges and bandages.

Elastic cotton-core nonwovens

The elastic nonwoven possesses extensibility in one direction which imparts the desired comfort and fit properties, enabling usage to applications such as inexpensive elastic leg cuffs and waist bands for disposable diapers, protective apparel, face masks, bandages.[53]

4.3.7 Chemical-bonded nonwovens

Many incontinence products are chemically bonded. These are often based on carded or airlaid webs and require a high rate of absorption, high capacity and

© Woodhead Publishing Limited, 2011

some softness. Very soft grades of styrene butadiene or self-cross-linking butyl acrylates are used.

Print-bonded fabrics are much softer in feel and also much more flexible owing to the strong effect of the free fibres in the unbonded areas. These are used in applications where the textile like handle is an advantage. Examples are disposable/protective clothing, coverstock and wiping cloths.[54,55]

4.4 Strengths and limitations of nonwoven materials (NMs) for medical applications

4.4.1 Strengths

NMs for medical applications stand out for numerous advantages they offer, both with regard to user requirements and material properties. Two characteristics of nonwovens make them particularly suitable for use in an absorbent structure: high bulk for imbibing and holding large amount of fluid per unit mass of material and low cost of converting raw material into final product. The advantages of using nonwovens in medical and healthcare are: protection against dry or wet contact, air-borne particles, fully compliant with EU standard EN 13795, single-use: 100% certainty, custom-made for the operating theatre, procedure-specific design, optimum wearer comfort, strong yet light in weight, optimal fluid absorbency, exchange of air, body heat and moisture, excellent barrier properties, excellent uniformity, breathability, abrasion resistance and lint free, repellency, self-adherent edges, aseptic folding, engineered stability for plasma, radiation or steam sterilisation.

Apart from the characteristics of comfort and kindness to the skin, the range of other special properties includes non-adherent compress surfaces and high absorbency. This helps make compresses ideal for the care of both dry and secretary wounds, since blood and secretions are passed on to the absorbent pad, because of the special fibre structure.[56]

Because sterilisation is a major concern for surgical dressings, nonwovens are preferred. Nonwovens can be smooth, and lint free for the most part. This allows for a lesser chance for debris to be left in the wound. Nonwovens can be made softer and more absorbent by latex or thermal calendering.[57] Nonwovens can be tailor-made with every required feature, such as excellent barrier properties, uniformity or breathability.

The features of nonwovens for backings and wound pads in wound dressings, for instance, are the particular advantages offered by the material: they are easy to process, permeable to air, non-adherent to wounds and are highly absorbent, they have a large surface area with no dust, and a surface mechanism which can readily be conditioned to serve as an excellent dressing material.[58]

SM SMS has excellent barrier properties coupled with adequate breathability to maintain personal comfort. This is due to a careful balance of the liquid impervious

© Woodhead Publishing Limited, 2011

barrier with adequate moisture vapour transmission characteristics. For example, the viral barrier gowns give protection from viruses, which are within the nanometre size range, and therefore protective films are used. In viral barrier gowns the permeation of moisture vapour is very important; that is, the rate at which the moisture vapour is passed through. So normally it is a three-layer structure: SMS, film and then SMS again. Films are non-porous but highly hydrophilic so the moisture vapour can pass through and the film is breathable.

These composite structures provide excellent abrasion resistance and lint-free properties beside effective barrier properties to many liquids including blood, other body fluids, alcohol, water, etc.[59] They guarantee the safety of patients and medical staff thanks to superior levels of infection control, sterility and efficiency.

4.4.2 Limitations

Nonwovens are known for their disposability. One way the nonwovens industry is marketing itself is by using the term 'single use' instead of 'disposable' products. Money is the greatest problem because many hospitals have much capital invested in laundry facilities, which does not allow for disposables.

The main limitations include: not reusable, lower resistance, poor drapeability, barrier to change to new draping systems. Traditional disposables, like hygiene and medical products, are in real trouble because of tighter environmental laws. There soon will be no more landfill sites to handle used disposables. Therefore, the big manufacturers of disposable products are looking more and more for biodegradable products. Responsibility has to become the key issue of economic, social and environmental activities. Modern wipes must have not only functional requirements, but also great flushability to disintegrate as quickly as possible. The industry is being challenged; every production stage, from fibre to finishing, must reinvest heavily in new production technologies. This is probably the 'squaring' of the circle and just another challenge for the very promising nonwovens industry.[60]

4.5 Applications of nonwovens in medicine

NMs are very important in all aspects of medicine and surgery and the range and extent of applications to which these are used is a reflection of their enormous versatility. Nonwoven products utilised for medical applications may at first sight seem to be either extremely simple or complex items. In reality, however, in-depth research is required to engineer a textile for even the simplest wipe in order to meet the stringent performance specifications.[61]

Medical nonwovens include drapes and gowns, sterile wraps, swabs (OR use and ward use) and dressings. Among them, surgical gowns, drapes and drape pack parts account for almost two thirds. Among product segment, surgical nonwoven products market is the largest and the fastest growing segment.[62] Surgical drapes

© Woodhead Publishing Limited, 2011

Table 4.1 Applications of nonwovens in non-implantable medical textiles

Product application
Wound care • Absorbent pad • Wound contact layer • Base material
Bandages • Simple inelastic/elastic • Light support • Orthopaedic
Plasters
Gauzes
Wadding
Medical • Transdermal drug delivery • Shrouds • Procedure packs • Heat packs • Ostomy bag liners • Incubator mattresses • Fixation tapes

made of NMs have captured about 95% of the total drapes market. Surgical gowns have captured an estimated 90% of the gown market.[63] Table 4.1 shows the applications of nonwovens in non-implantable medical textiles.[64–77]

4.5.1 Wound care products

NMs have been used rather extensively as the facing, as well as the entire absorbent pad of a wide variety of wound dressings and surgical pads.[78] Over many years, there has been a growing interest in the use of spunlace NMs in a broad range of dressings, surgical sponges, surgical pads, and similar important healthcare products. A widely used fabric for this application has been a spunlace web derived from 70% rayon and 30% polyester in approximately 70 g/m^2 weight. This fabric folded into a 4-ply sponge, has been able to replace the earlier 16-ply woven gauze sponge with equivalent absorbency, less linting, and softer hand. An absorbent thermally bonded nonwoven web has also been offered as a surgical sponge.

Needle punch fabrics from hydrophilic, hydrophobic and blends of fibres have been used for absorbent applications in dressing products. The nonwoven fabric made from chitin fibres can be used as an artificial skin for treating burn wounds.[79,80] Nonwoven fabrics made of atelocollagen filaments are also used as

© Woodhead Publishing Limited, 2011

wound dressing for burns. For postoperative dressing, sophisticated nonwoven structures such as perforated film on absorbent base, polymer/nonwoven welded laminate and metallised nonwoven fabric are used.

A nonwoven fabric of regenerated collagen has been commercialised for wound covering. To manufacture alginate nonwoven dressings alginate fibres are separated, carded and layered to form a continuous 'nonwoven' fabric. In some cases, this fabric is subjected to needling to strengthen the fabric. The entanglement of fibres by needling will increase both wet and dry fabric strength and therefore the likelihood that a dressing will remain in one piece during use and removal. Softness and conformability are imparted due to the fabric's fibrous construction. A typical 10×10 alginate dressing contains 100 000 individual fibres each of around 15 μm diameter which, if placed end-to-end, would stretch for 5 kilometres. Absorption of wound fluid is enhanced by the high surface area of the material and by the wicking action of the fabric. Nonwovens are very bulky fabrics with a low density; a typical alginate dressing contains about 90% free space. This space can rapidly disappear, however, as filaments swell to many times their original diameter during gelling. Absorption of wound fluid is enhanced by the filling of the spaces between fibres. Sorbsan and Sorbalgon are examples of dressings where fibres are not interlocked. Algisite M is an example of a heavily needled fabric. Alginate dressings absorb up to 20 times their own weight of test fluid. They absorb far more rapidly than hydrocolloid dressings and are able to be used in combination with secondary dressings to increase absorption capacity still further. Studies in comparison with hydrocolloid dressings have shown alginates to be superior in terms of fluid handling, gel-blocking, pain control and healing properties.[81–85]

Some other examples are: Vilmed® nonwovens for wound pads are thermally bonded, Vilmed® nonwovens used as backings for wound dressings and plaster strips, Vilmed® adhesive tape substrates are made from wet-laid nonwovens and have been successfully used for years in the medical dressings industry as they are put into use in clinical applications every day, for example to secure dressings or tubes, Vilmed® orthopaedic cast paddings, made of synthetic fibres without bonding agents. Optimum stretch properties prevent constriction when bandaging, air permeability ensures a pleasant microclimate under the dressing. These positive qualities offer an advantage in padding for rigid dressings, support bandages, and compression bandages or for splints.[86]

4.5.2 Medical gauze

With spunlace technology cost competitive low grammage gauze products are produced where the open structure is formed by the selection of a wire mesh for spunlacing, i.e. the web takes the structure of the wire mesh. Moreover, only 4 instead of the 6–16 layers are usually required for nonwovens gauze which also adds to cost saving.[87] Commercially, spunlaced gauze fabrics composed of 70% viscose rayon and 30% polyester provide high absorbency and low lint properties.

© Woodhead Publishing Limited, 2011

4.5.3 Wadding

Wadding is a highly absorbent material that is covered with a nonwoven fabric to prevent wound adhesion or fibre loss. Nonwoven orthopaedic cushion bandages are used under plaster casts and compression bandages for padding and comfort. These may be produced from either polyurethane foams, polyester or PP fibres and contain blends of natural or other synthetic fibres. Nonwoven bandages made of viscose are lightly needle-punched to maintain bulk and loft.[88] As well as providing padding, nonwoven orthopaedic cushion bandages must be soft and drape well. It must also be possible to tear the bandage off and they must adhere to one another. The bonding of the surface must be strong enough to allow the fabric to be handled by wet fingers without fluff forming. The cross-laid nonwoven bonded fabrics available on the market have an area weight of about 70 g/m^2 and are made from fibre-fill fibres of between 6 and 12 dtex. They are either fibre-bonded materials or are spray bonded with acrylics. A development in cushion bandage materials includes a fully engineered needle punched structure which possesses superior cushion properties compared with existing materials.

Table 4.2 depicts the applications of NMs in the healthcare/hygiene sector of medical textiles.[89–94] NMs are being increasingly used in hospitals although disposability of single-use products pose environmental concerns.

4.5.4 Surgical gowns

Disposable nonwoven surgical gowns have been adopted to prevent the release of pollutant particles into the air which is a probable source of contamination to the patient. The need for a reusable surgical gown that meets the necessary criteria has resulted in the application of fabric technology adopted for clean room environments. Single use nonwoven medical drapes and gowns are becoming the first choice of healthcare professionals because they feel they are superior to reusables. They have confidence that they will be protected from infection.[95,96] Surgical gowns are composed of nonwoven fabrics and polyethylene films in weight range of 30–45 g/m^2.

The general requirements for surgical drapes and gowns include liquid repellency and bacterial barrier properties,[97,98] aesthetics (including conformability, tactile softness, comfort), strength, fibre tie-down properties (lint propensity and abrasion resistance), flame resistance, static safety and toxicity. For surgical drapes, stiffness is very critical because barrier performance may be affected by conformability to patient or equipment. For gowns, comfort and stiffness may affect perspiration and movement. Strength requirements include tensile, tear, burst and puncture resistance. Linting is not wanted because particles from gown or drape may complicate the wound healing process.

© Woodhead Publishing Limited, 2011

Table 4.2 Applications of nonwovens in the healthcare/hygiene sector of medical textiles

Product application
Surgical clothing
• Gowns
• Caps
• Masks
Surgical covers
• Drapes
• Cloths
Clothing
• Protective clothing
Personal care/hygiene
• Baby diaper
• Feminine hygiene
• Training pants
• Cosmetic removal pads
• Nursing pads
• Nasal strips
• Adhesive for dental plates
• Disposable underwear
Incontinence diaper/sheet
• Cover stock
• Absorbent layer
• Outer layer
Clothes/wipes

Nonwoven drapes and gowns have four levels of barrier performance. Here are examples of the types of materials that are used in gowns:

Level 1: SB PP and Spunlace PET/Woodpulp – very light material meant to be used where there is little to no contact with blood or bodily fluid.

Level 2: Medium weight SMS and Spunlace PET/Woodpulp – made out of three or more layers providing a more comfortable/breathable barrier. Used in cases of light contact with blood and bodily fluids.[99]

Level 3: Heavy weight SMS – made out of three (or more SSMMMSS – seven layers) layers providing a more comfortable/breathable barrier. Used in cases of moderate exposure to blood and bodily fluids.

Level 4: Poly coated – made from SMS PP or Spunlace PET/Woodpulp material coated with PE. PP is light and comfortable and PE gives a strong barrier to fluids. Used when high contact with blood and bodily fluids is expected.

Plasma treatment can provide a good barrier against blood and water, and can even provide a barrier against microbes, which makes it a better finish for surgical gowns.[100] Fabric can be treated with antibiotic and fluorochemical should be used for functional surgical gowns.[101]

© Woodhead Publishing Limited, 2011

4.5.5 Surgical caps

The caps must be comfortable to wear, i.e. the material must be soft, pliable, air permeable, absorbent, virtually lint free and also sterilisable, even though headgear is not normally sterilised. Nonwoven surgical caps are made of cellulosic fibres with the parallel-laid or spunlaid process in range of 17–20 g/m^2.

4.5.6 Surgical masks

The characteristics required of operating masks need defining more clearly. The wearer expects comfort, i.e. good fit, a high level of air permeability, softness, lightness in weight and skin compatability, whilst providing the highest possible filter capacity.[102]

A disposable surgical mask is expected to protect 98% of the bacteria from reaching the user, and has to be waterproof, therefore SMS structures are used. It consists of a very fine middle layer of extra fine glass fibres or synthetic micro-fibres covered on both sides by either an acrylic bonded parallel-laid or wet-laid nonwoven. The thickness of the fibre is between <1 and about 10 µm and the area weight of this middle layer is between 10 and 100 g/m^2 depending on the method of manufacture, structure of the web, the cross-sectional shape of the fibre and its charge. PP, polystyrene, polycarbonate and other polymer fibres are suitable substitutes for extra-fine glass fibres. The surface filter layer is composed of micro-fibres of glass, polyester, PP or polycarbonate with a diameter of 4 and 8 µm. MB fabrics can be used for surgical face mask filters.

4.5.7 Drapes and cover cloths

In the operating room, the success of surgery is a combination of several factors and choosing the right material for a surgical drape is one of them. Fabric barrier and strength are key requirements for surgical drapes, yet other properties such as drapeability and linting must be taken into account to protect the patient and not interfere with the surgery process.[103] Both spunlaced and spunlaid composites are used for drapes and cover cloths. Nonwovens are used as backing material on one or both sides of a film which is completely impermeable to bacteria while the nonwoven backing is highly absorbent to both body perspiration and secretions from the wound. A typical isolation and cover gown consists of a single layer SB basic cover or a three-layer SMS fabric for increased barrier properties, softness and comfort.

4.5.8 Bed linen

It would be desirable for disposable nonwovens to be used as bed linen in hospitals to break the chain in the spreading of infection. They are often used in operating rooms but seldom for bed linen, except in casualty departments and isolation wards and are commonly used as incontinence sheets.[104]

© Woodhead Publishing Limited, 2011

4.5.9 Clothing

Clothing products, which include articles worn by both nursing staff and patients, have no specific requirements other than comfort and durability. In isolation wards and intensive care units, disposable protective clothing is worn to minimise cross-infection. A wide range of designs in various types of nonwoven fabric is available as head coverings for male and female staff. These articles are made from composite fabrics that consist of tissue reinforced with a polyester or PP spun-laid web. SMS and wet laid are the major nonwoven types used in sterilisation wrap, laboratory coats, jackets and coveralls.

4.5.10 Incontinence products

Single-use incontinence products absorb and lock away urine and faeces so that leakage does not occur and the user's skin is kept dry and healthy. Incontinence products for the patient are available in both diaper and flat sheet forms with the latter used as bedding. The disposable diaper is a composite article consisting of an inner covering layer (coverstock), an absorbent layer and an outer layer.[105]

Coverstock is a generic used to describe the several NMs used in hygiene products' construction of about 18–85 g/m^2, which includes topsheet, barrier leg cuff, back sheet, stretchy panels, fastening and landing strips, ADL and airlaid pulp absorbent core materials.[106] It is either a longitudinally oriented polyester web treated with a hydrophilic finish, or a spun-laid PP NM used to contain and conceal an underlying core material. Examples include facing materials that cover the absorbent cores of diapers, sanitary napkins and adult incontinence products.[107,108] Carded thermobonded nonwoven fabrics made with hydrophilic PP fibres in grammage ranging from 16 to 30 g/m^2 are able to guarantee rapid fluid passage while maintaining contact with the surface of the skin and keep it dry and comfortable.[109–112]

NMs used in baby diapers as top sheet are either 100% SB or thermal bonded PP.[113] Carded products have been replaced by SB due to its cost effectiveness and other unique technical properties. Recent developments in polymer and web forming technologies have improved web softness and can potentially reduce weights.[114] The current incontinence pad has SAP, which helps to reduce the leakage, hence increases the dryness and comfort. Comfort improvement, discretion and cost improvement on storage and transportation will eventually gear its course towards thinner products.[115]

4.5.11 Cloths and wipes

In this era of convenience, the ultimate item is a wet wipe. In the personal care arena, wipes can be used for almost anything.[116] One of the most obvious requirements for a wiping product is rapid absorbency.

© Woodhead Publishing Limited, 2011

There are three basic nonwoven technologies that are helping spur on the growth in the wipes category. These are airlaid, spunlace and to a lesser degree SB MB laminates. Wipes are made from tissue paper or spunlaced nonwoven fabrics from PP in blend with viscose/rayon in the range of 30–70 g/m^2 weight which may be soaked with an antiseptic finish.[117]

4.5.12 Feminine sanitary napkins

In feminine sanitary napkins topsheet fabric is lighter than the coverstock used on an infant diaper. In fabrication of the absorbent core such as Oasis SAF®[118] there is a growing use of preformed airlaid pulp fabric to replace the current wood pulp fibre core. The airlaid pulp fabric can be supplied and used on the converter line directly, eliminating the large, noisy, and dusty pulp sheet grinding operation.[119]

4.5.13 Underpads

Underpads are a very important part of care of people with urological problems. Underpads are designed in an extra large size, 30 × 36 inches, to protect a large area of bed, reducing bedding changes and laundry costs. Lightweight rayon dry form topsheet was the industry standard for many years. SB nonwoven topsheet made of polymers allows fluid to pass through quickly to the core which ensures comfort and the underside is secured with anti-skid and waterproof layer, which prevent the underpad from moving on sheet and does not allow any liquids to get out of it. Lightweight fabrics produced via the wet form process have also been used. In such cases, the nonwoven fabric has generally been produced from a blend of wood pulp and short cut polyester fibre in varying proportions. Latex print bonding has normally been employed for these structures.[120]

4.5.14 Tampons

Modern tampons (over 90%) are mainly composed of cellulosic absorbent material, either rayon or cotton or a mixture of these fibres and worldwide this has been the case for many decades. Some other absorbent materials were introduced into tampons in non-European countries, but these disappeared after a period of time, whereas the cellulose based tampons always remained on the market.

In most instances, the absorbent core is covered by a thin, smooth layer of nonwoven or perforated film helping to reduce loss of fibres and making the tampon easy to insert and remove. The withdrawal cord that is necessary to remove the tampon is usually made of cotton or other fibres and can be coloured.[121] A light carded bicomponent nonwoven may be used as a soft coverstock.[122]

© Woodhead Publishing Limited, 2011

4.5.15 Tissue engineering

Tissue engineering merges the fields of cell biology, engineering, materials science and surgery to fabricate new functional tissue using living cells and a matrix or scaffold. Resorbable spunlaid nonwovens are used increasingly as a substrate for 3D tissue engineering, such as chondrocytes, endocrine cells, and as patches to cover larger areas of injured tissue. Nonwovens have a high porosity which allows permeation and growth of cells *in vitro* and *in vivo*. To construct a comfortable and porous 3D scaffold structure, with macrostructural features that are characteristic of cartilage NMs are made from fibres (length to breadth ratio > 1000:1) or continuous filaments based on resorbable or non-resorbable synthetic and natural polymers. The fibres or filaments are assembled in to a web structure whose geometry is characterised by packing density, pore size distribution and the *x*, *y* and *z* orientation of the fibre components.[123–125] A nonwoven fibrous mat made of graphite and teflon is used around the orthopedic implant to promote tissue growth.

4.6 Future trends

The big challenge among airlaid producers as well as end use manufacturers in the hygiene market will be educating consumers to the merits of a thinner material in absorbent products. This goal has already been achieved in feminine hygiene products with women now trusting thinner pads to absorb their menstrual flows. Now the challenge remains in the adult incontinence and baby diaper markets where producers need to prove that thinner airlaid cores can, in fact, handle urinary flow. The issue of proper comprehension of nonwovens disposable applications in medical industry among consumers in various countries is likely to influence the market. Countries with low awareness about the product's medical usage would experience low market development, thereby limiting the overall market growth. Along with increasing personal incomes, the consumption of disposables, such as medical and hygiene products, will definitely rise. Disposable external feminine hygiene products are an essential part of modern lifestyles, and will continue to be for the foreseeable future.

Because of the increasing awareness by healthcare professionals and medical advisors and the still untapped potential in many European markets, single-use products are becoming commonplace. The safety of patients, staff and carers is on the forefront for these developments. Organisations like WHO, ECDC, EORNA (European Operating Room Nurses Association) and local health authorities emphasise stricter hygiene protocols when dealing with the prevention of infection.

Innovation and technology will enable the industry to continue to observe sustainability in the production of even higher performance products to meet the needs and increasing expectations of consumers. With increasing skill on the part

© Woodhead Publishing Limited, 2011

of the fibre technologists to create fibrous precursor webs, including composites with specific orientation and configuration of fibres, the possibility grows for engineering fibrous structures specifically designed to enhance and control absorbency characteristics. Bicomponent splittable or fibrillated fibres, nanotechnology and fibre modification also play important roles in some recent developments, a number of them involving filtration and barrier technologies. Nonofibres are becoming very popular for medical textiles used to filter viruses and bacteria.

4.7 Sources of further information and advice

- EDANA, 157 Avenue Eugène Plasky, B-1030 Brussels, Belgium
- Oerlikon Neumag, Zweigniederlassing der Oerlikon Textile GmbH & Co. KG Christianstraße 168–170, D-24536 Neumünster, Germany. Tel: +49 4321 305 0XX; Fax: +49 4321 305 212
- Fleissner GmbH 2010, 63329 Egelsbach, Germany
- Svetlogorsk PA Khimvolokno, Zavodskaya 5, 247434, Svetlogorsk, Gomel reg, Republic of Belarus; Tel.: +375 2342 94865, Fax: +375 2342 70270
- Speciality Fibres and Materials Ltd, P.O. Box 111, 101 Lockhurst Lane, Coventry CV6 5RS, UK. Tel: +44 (0) 2476 708200; Fax: +44 (0) 2476 682737; E-mail: enquiries@sfm-limited.com www.sfm-limited.com

4.8 References

1 Sayed U, Pratap M R and Rane Y N (2002). The use of textile fibres in the medical sector, *Asian Text J*, June, 67–75.
2 Kocak D, Akalin M, Usta I and Merdan N (2006). New approach to produce absorbent pads for new ends uses, in *Medical Textiles and Biomaterials for Healthcare*, ed. by Anand S C, Kennedy J F, Miraftab M and Rajendran S. Woodhead Publishing Ltd, Cambridge, pp. 320–326.
3 Anon (2008). More than a partner for nonwovens development, *Customer Magazine of Rieter Nonwovens Systems* No. 5, April, 3.
4 Gupta B S and Smith D K (2002). Nonwovens in absorbent materials, in *Absorbent Technology*, ed. by Chatterjee P K and Gupta B S. Elsevier Science, pp. 350–376.
5 Anand S C (2006). Healthcare & hygiene products: An overview, in *Medical Textiles and Biomaterials for Healthcare*, ed. by Anand S C, Kennedy J F, Miraftab M and Rajendran S. Woodhead Publishing Ltd, Cambridge, pp. 75–79.
6 Prescott B A, Anand S C, Richards A F and Halfpenny J R (2001) Cotton-blend nonwoven fabrics for medical use, *Text Asia*, January, 45–48.
7 Karthik T (2004). Barrier fabrics of spunbond speciality fibres for medical applications, *Synth fibres*, July–September, 7–9.
8 http://www.libeltex.com.
9 Hongu T, Phillips G O and Takigami M (2005). *Fibers in Medical Healthcare, New Millennium Fibers*, Woodhead Publishing Ltd, Cambridge, pp. 247–268.

© Woodhead Publishing Limited, 2011

10 http://www.lenzing.com/fe/media/LB-0842005042.pdf.
11 http://www.ciba.com/ind-pla-tex-app-hygiene___medical.
12 www.rieter.com.
13 Rupp J, Nonwovens Focus: Human-centered Applications, http://www.textileworld.com/Articles/2010/March/Issue.
14 Anon (2006). ISOjetTM offering higher value, *The Customer Magazine of Rieter Nonwovens Systems,* No. 2. October, 3.
15 Rupp J, Spunlaced Or Hydroentangled Nonwovens, www.textileworldasia.com/Articles/2008/October_2008.
16 Wubbe E, Innovations boosts spunlace, http://www.nonwovens-industry.com/articles/2003/03.
17 Rajendran S (2006). Infection control and barrier materials: An overview, in *Medical Textiles and Biomaterials for Healthcare*, ed. by Anand S C, Kennedy J F, Miraftab M and Rajendran S. Woodhead Publishing Ltd, Cambridge, pp. 131–135.
18 Rupp J, Recent Developments In Spunlacing, http://www.textileworldasia.com/Articles/2010/May/April_May_June_issue.
19 Glawion E (2006). MB and SB systems for PET, *Man-Made Fiber Year Book* 2006, pp. 99–101.
20 Non-woven machinery technical specifications – China Textile Machinery (Group) Co., Ltd.
21 Starr J R (2000). Nonwovens in hygiene and medical applications, *Nonwovens Industrial Textiles*, 3, 8–9.
22 Anand S C and Brunnschweiler D (2007). Mechanical bonding, in *Handbook of Nonwovens*, ed. by Russell S J. Woodhead Publishing Ltd, Cambridge, pp. 201–297.
23 Kamath M G, Atul D and Raghavendra R H, Spunlacwe (hydroentanglement), www.engr.utk.edu/mse/Textiles/Spunlace.htm.
24 Anon (2006). *Global Market Trends for Nonwovens*, *Man-Made Fiber Year Book*, p. 108.
25 http://www.sohim.by.
26 Anon (2006). SPUNjet® – A Rieter solution for spunlaid nonwovens, *The Customer Magazine of Rieter Nonwovens Systems*, No. 2. October, 8.
27 Geus H G (2008). Future of SB and MB technologies, *Chem Fiber Int*, 3, 133.
28 www.reicofil.com.
29 www.toray.com.
30 Anon (2006). Fitesa successful with spunbond fabrics, *The Customer Magazine of Rieter Nonwovens Systems*, No. 2. October, 10–11.
31 Bhat G S (2007). Polymer-laid web formation, *Handbook of Nonwovens*, ed. by Russell S J. Woodhead Publishing Ltd, Cambridge, pp. 143–200.
32 Maggio I R and Guichon O (2001). A new spunbond technology for new products, *Nonwovens Industrial Textiles*, 3, 68–69.
33 Anon (2008). In search of lower basis weight fabrics in spunbond, *The Customer Magazine of Rieter Nonwovens Systems*, No. 5, April, 8–9.
34 Rupp J, Spunbond and Meltblown Nonwovens, Nonwovens/Technical Textiles, www.textileworld.com/Articles/2008.
35 Expert Committee on Technical Textiles, Proceedings of a seminar on 'Technical textiles an emerging business opportunity', 25 February 2004, organised by the Man-made Weaving Industry Welfare & Relief Trust jointly with the Surat Art Silk Cloth Manufacturers Association, Surat, Gujarat, India, pp. 64–83.
36 Madhavamoorthi P and Shetty G S (2005). *Manufacturing Technology For Nonwovens*, Mahajan Publishers Pvt. Ltd, India, pp. 109–223.

© Woodhead Publishing Limited, 2011

37 Brydon A G (2007). Dry-laid web formation, *Handbook of Nonwovens*, ed. by Russell S J. Woodhead Publishing Ltd, Cambridge, pp. 16–111.
38 www.neumag.oerlikontextile.com.
39 Bitz K (2001). Much ado about airlaids, http://www.nonwovens-industry.com/articles/2001/10.
40 Kadam S C, Nonwoven fabrics: raw materials, production processes/technologies, product applications, in Proceedings of a National Seminar on 'Nonwoven fabrics: raw materials, production technologies and applications', organised by the Institution of Engineers (India), on 27–28 September 2005, Surat, India, pp. 40–59.
41 Knowlson R (2001). Airlaid products investments in the future, http://www.nonwovens-industry.com/articles/2001/10/.
42 www.rexcell.se.
43 www.plastics-technology.com.
44 Purdy A T (1983). Thermal Bonded fabrics, in *Developments in Non-Woven Fabrics*, The Textile Institute, 67–76.
45 Pourmohammadi A (2007). Thermal bonding, in *Handbook of Nonwovens*, ed. by Russell S J. Woodhead Publishing Ltd, Cambridge, pp. 298–329.
46 Karve M, Technical textiles: an emerging business opportunity, in Proceedings of a National Seminar on 'Nonwoven fabrics: raw materials, production technologies and applications', organised by the Institution of Engineers (India), on 27–28 September 2005, Surat, India, pp. 25–39.
47 Watzl A (2006). Spunlace/airlaid combination for cost saving in medical and hygiene nonwovens, *Indian Text J*, April, 69–72.
48 Watzl A and Eisenacher J (2000). Spunlace process for cotton pads and other products, *Nonwovens Ind Text*, 3, 16–18.
49 Muhammad Kamran Iqbal, The applications of nonwovens in technical textiles, www.ptj.com.pk/Web-2009/12-09.
50 www.avgol.com.
51 www.ahlstrom.com.
52 Anon (2000). Refenhäuser technologies for SB and MB nonwovens, *Chem Fibers Int*, 50, 169–171.
53 Anon (2002). Cotton core nonwovens, *Asian Text J*, June, 23–24.
54 Smith P A (2000). Technical fabric structures – Nonwovens fabrics, in *Handbook of Technical Textiles*, ed. by Horrocks A R and Anand S C. Woodhead Publishing Ltd, Cambridge, pp. 130–151.
55 Chapman R A (2007). Chemical bonding, in *Handbook of Nonwovens*, ed. by Russell S J. Woodhead Publishing Ltd, Cambridge, pp. 330–367.
56 Sakthivel S, Prakash S and Karthikeyan L (2010). Progressive nonwovens offer price-friendly options, *ATA J Asia Text Apparel*, Apr 2010 Issue, available: www.adsaleata.com.
57 S. Adanur S (1995). Medical textiles, in *Wellington Sears Handbook of Industrial Textiles*, Technomic Publishing Company, Inc., USA, pp. 329–355.
58 Ching Wen Lou *et al*. (2008). Properties evaluation of tencel/cotton nonwoven fabric coated with chitosan for wound dressing, *Text Res J*, 78(3), 248–253, doi: 10.1177/004517507089747.
59 http://www.mogulsb.com.
60 Rupp J, Nonwovens: Challenges and trends, http://www.textileworld.com/Articles/2009/December/NW.

© Woodhead Publishing Limited, 2011

61 Bealer Rodie J (2009). Innovations in the growing nonwoven medical textiles sector include new products aimed at infection prevention, available: www.textileworld.com/Articles/2009/July/NWTT.
62 Anon (2008). Study charts disposable medical applications, *Nonwoven Tech Text*, January–March 65.
63 Anon, The evolving roles of nonwovens in technical textiles, http://goliath.ecnext.com/coms2/gi_0199-7723246.
64 Sayed U, Pratap M R and Rane Y N (2002). The use of textile fibres in the medical sector, *Asian Text J*, June, 67–75.
65 Miraftab M, Smart G, Kennedy J F, Knill C J, Mistry J and Groocock M R, Novel chitosan-alginate fibers for advanced wound dressings, in *Medical Textiles and Biomaterials for Healthcare*, ed. by Anand S C, Kennedy J F, Miraftab M and Rajendran S, Woodhead Publishing Ltd, Cambridge, pp. 37–49.
66 Ajmeri C J and Ajmeri J R (2006). Application of nonwovens in healthcare and hygiene sector, in *Medical Textiles and Biomaterials for Healthcare*, ed. by Anand S C , Kennedy J F, Miraftab M and Rajendran S, Woodhead Publishing Ltd, Cambridge, pp. 80–89.
67 http://www.johnrstarr.com.
68 Madhavamoorthi P and Shetty G S (2005). Fibers used for nonwovens, *Nonwoven*, India, Mahajan Publishers Pvt. Ltd, India, pp. 14–82.
69 Lshanmugasundaram O L (2008). Applications of nonwovens in medical field, *Indian Text J*, September, pp. 99–104.
70 Edward Menezes E (2008). Nonwovens, *Nonwoven Tech Text*, January–March, 33–38.
71 Shishoo R (2001). Future developments in fibres, yarns and fabrics for technical applications, *Nonwovens Ind Text*, 3, 24–29.
72 Singh S, Nonwoven fabrics: a business opportunity, in Proceedings of a National Seminar on 'Nonwoven fabrics: raw materials, production technologies and applications', organised by the Institution of Engineers, on 27–28 September 2005, Surat, India, pp. 1–12.
73 Naik D V and Shah K C, An introduction to nonwoven fabric world, in Proceedings of a National Seminar on 'Nonwoven fabrics: raw materials, production technologies and applications', organised by the Institution of Engineers (India) on 27–28 September 2005, Surat, India, pp. 60–66.
74 Bhat S and Mahale G (2000). Textiles in health & medical applications, *Man-made text India*, April, 185–189.
75 Wilson A (2010). The formation of dry, wet, spunlaid and other types of nonwovens, in *Applications of Nonwovens in Technical Textiles*, ed. by Chapman R A. Woodhead Publishing Ltd, Cambridge, pp. 3–17.
76 Bhat G and Parikh D V (2010) , Biodegradable materials for nonwovens, in *Applications of Nonwovens in Technical Textiles*, ed. by Chapman R A. Woodhead Publishing Ltd, Cambridge, pp. 46–62.
77 Ajmeri J R and Ajmeri C J (2010). Nonwoven personal hygiene materials and products, in *Applications of Nonwovens in Technical Textiles*, ed. by Chapman R A. Woodhead Publishing Ltd, Cambridge, pp. 85–102.
78 Arun N (2002). Medical textiles: a unique agenda in medical network, *Synth fibres*, April– June, 14–16.
79 Anandjiwala R D (2006). Role of advanced textile materials in healthcare, in *Medical Textiles and Biomaterials for Healthcare*, ed. by Anand S C , Kennedy J F, Miraftab M and Rajendran S. Woodhead Publishing Ltd, Cambridge, pp. 90–98.

© Woodhead Publishing Limited, 2011

80 Ikada Y (1989). Bioabsorbable fibers for medical use, in *High Technology Fibers, Part B*, ed. by Lewin M and Preston J. Marcel Dekker, Inc., New York, pp. 253–302.
81 www.specialityfibres.com.
82 Mathur M and Hira M A (2005). Speciality fibres III: alginate fibre, *Man-made Text India*, August, 294–299.
83 Sathivel J *et al*. (2006). Health and comfort fibres, *Man-made text India*, June, 217–221.
84 Vijayaraaghavan N N and Gopalakrishnan D (2005). Alginate fibres, *Synth fibres*, October–December, 4–8.
85 Niekraszewicz B and Niekraszewicz A (2009). The structure of alginate, chitin and chitosan fibres, in *Handbook of Textile Fibre Structure*, ed. by Eichhorn S J, Hearle J W S, Jaffe M and Kikutani T. Woodhead Publishing Ltd, Cambridge, pp. 266–306.
86 http://www.nonwovens-group.com.
87 www. spuntech.com.
88 Basu S K *et al*. Medical textiles: fibres, technology and products, in Proceedings of a National Seminar on 'Medical textiles: Production technologies and applications' organised by the Instituion of Engineers (India), October 2007, Surat, pp. 55–66.
89 Arun N (2001). Technical textiles: Materials and methods of manufacture, *Indian Text J*, March, 15–24.
90 Ajmeri J R and Ajmeri C J (2002). Special textiles for industry applications, *Text Magazine*, October, 70–72.
91 Anand S C (2006). Implantable devices: an overview, in *Medical Textiles and Biomaterials for Healthcare*, ed. by Anand S C, Kennedy J F, Miraftab M and S Rajendran S. Woodhead Publishing Ltd, Cambridge, pp. 329–334.
92 Rigby A J and Anand S C (2000). Medical Textiles, in *Handbook of Technical Textiles*, ed. by Horrocks A R and Anand S C. Woodhead Publishing Ltd, Cambridge, pp. 407–424.
93 Teli M D, Functional textiles & apparels, in Proceedings of 9th International & 63rd All India Textile Conference 2008, 'Advantage India – Textiles & Apparels', organised by The Textile Association (India), 5–6 January 2008, A'bad, India, pp. 120–136.
94 Jaipuria S, Medical textiles: Futures is nonwoven, in Proceedings of a National Seminar on 'Medical textiles: Production technologies and applications' organised by The Textile Association (India), October 2007, A'bad, India, pp. 14–24.
95 http://www.inda.org/enduses/hlthbro/DrapesandGowns.html.
96 Leaonas K K (2005). Microorganism protection, in *Textiles for Protection*, ed. by Scott R A, Woodhead Publishing Limited, Cambridge, 441–464.
97 Huang W and Leonas K K (2000). Evaluating a one-bath process for imparting antimicrobial activity 7 repellency to nonwoven surgical gown fabrics, *Text Res J*, 70(9), 774–782.
98 Collier B J (2010). Nonwovens in specialist and consumer apparel, in *Applications of Nonwovens in Technical Textiles*, ed. by Chapman R A. Woodhead Publishing Limited, Cambridge, pp. 120–135.
99 Fisher G (2006). Development trends in medical textiles, *ATA J Asia Text Apparel*, February. Available: www.adsaleata.com.
100 Virk R K and Ramswamy G N (2004). Plasma and antimicrobial treatment of nonwoven fabrics for surgical gowns, *Text Res J*, 74(12), 1073–1079.
101 Jeong-Sook Cho and Gilsoo choo (1997). Effect of a dual function finish containing an antibiotic & a fluorochemical on the antimicrobial properties & blood repellency of surgical gown materials, *Text Res J*, 67(12), 875–880.

© Woodhead Publishing Limited, 2011

102 Ghosh S (2000). Medical Textiles, *Indian Text J*, March, 10–14.
103 Rakshit A K and Hira M A (2000). Developments in healthcare textiles, *Man-made text India*, January, 21–25.
104 Fahrbach E *et al*. (1985) Properties and end uses of nonwoven bonded fabrics, in *Non-woven Bonded Fabrics*, ed. by Lünenschloss J and Albrecht W. Ellis Horwood Ltd, Chichester, pp. 393–463.
105 Kung Hwa Hong, Soo Chang Kim and Tae Jin Kang (2005). Effect of abrasion and absorbed water on the handle of nonwovens for disposable diapers, *Text Res J*, 75(7), 544–550. doi: 10.1177/0040517505053856.
106 www.nsc.fr.
107 www.edana.org.
108 Malik A (2001). Polymers and fibres in disposable medical products, *Asian Text J*, January, 36–40.
109 www.curabody.com.
110 http://www.sandler.de.
111 http://www.albisnw.com.
112 www.bbanonwovens.se.
113 www.fiberweb.com.
114 http://www.generalnonwovens.com.
115 Chatterjee P K (2002). Products and technology perspective, in *Absorbent Technology*, ed. by Chatterjee P K and Gupta B S, Elsevier Science, London, pp. 448–475.
116 Bennett S, Kelly D, Kaziska A, Chandler M and Eaton C, Wipes: they are not just for babies anymore, www.nonwovens-industry.com/wipes/2010/04.
117 www.fibervisions-a-s.
118 www.techabsorbents.com.
119 http://www.nonwoven.co.uk/reports/NTC%202002%20contents.html.
120 http://www.premierenterprises.in/hygiene-products.html.
121 http://www.ahpma.co.uk.
122 Katzer K (2002). Polyethylene polymers for hygiene market, *Asian Text J*, June, 30–34.
123 Minns R J, Russell S, Young S, Bibb R and Moliter P (2006). Repair of articular cartilage defects using 3-dimensional tissue engineering textile architectures, in *Medical Textiles and Biomaterials for Healthcare*, ed. by Anand S C, Kennedy J F, Miraftab M and Rajendran S. Woodhead Publishing Ltd, Cambridge, pp. 335–341.
124 Gellynck K, Verdonk P, Almqvist F, Van Nimmen E, De Bakker D *et al*. (2006). A spider silk supportive matrix used for cartilage regeneration, in *Medical Textiles and Biomaterials for Healthcare*, ed. by Anand S C, Kennedy J F, Miraftab M, and Rajendran S. Woodhead Publishing Ltd, Cambridge, pp. 350–354.
125 Edwards S L, Russell S J, Ingham E, Mathews J B and Mitchell W, Nonwoven scaffolds of improved design for the tissue engineering of the anterior cruciate ligament, in *Medical Textiles and Biomaterials for Healthcare*, ed by Anand S C, Kennedy J F, Miraftab M and Rajendran S. Woodhead Publishing Ltd, Cambridge, pp. 355–365.

© Woodhead Publishing Limited, 2011

5

Textiles for implants and regenerative medicine

M. DOSER and H. PLANCK,
German Institute for Textile and Fiber
Research Denkendorf (DITF), Germany

Abstract: This chapter gives an overview of textiles that are used in medicine as implants and for regenerative medicine. The most relevant devices based on textile structures are described in detail, such as meshes for hernia repair and vascular prostheses for implantation as well as cartilage, nerve and liver regeneration. The advantages of different structures and materials are discussed and current trends in device development as well as regulatory aspects will be described.

Key words: textile implants, regenerative medicine, vascular prostheses, hernia meshes.

5.1 Introduction

Fibres and textiles have probably been used for medical applications since human beings learned to produce tools, mainly for wound care applications like sutures and wound dressings. In contrast it is not widely known that textile structures are used as permanent implants. In recent years they have even become an interesting material in the new field of regenerative medicine, which revolutionises many traditional therapies. The limited attention given to textiles for implantation is not justified because textiles are for many reasons significantly more suitable for use as implants compared to metals, for example. The human body is full of fibres (mainly collagen within the connective tissue, but muscles, tendons and nerves are also of fibrous nature) and so cells are used to handling these structures whereas a rigid block of a metal is generally difficult to integrate into the existing tissue.

This chapter will look more closely at fibrous structures to be used in implants and also in the new and fascinating field of regenerative medicine, where textiles are mainly used as cell carrier materials or sometimes as guiding materials in the process of tissue regeneration. The problems in obtaining appropriate fibres and in modifying them for medical applications will also be addressed along with general regulatory aspects: the requirements are completely different compared to other technical areas in which textiles are used, e.g. fibre reinforced materials.

© Woodhead Publishing Limited, 2011

5.2 Textiles as implants

5.2.1 Advantages, fields of application, materials

Natural fibres may have been used for medical applications for as long as mankind has existed. The use of silk for suturing open wounds, for instance, was already established in ancient Egypt and sutures are still the most important surgical textile structures. Compared to metals and ceramics, which are mainly used in osteosynthesis and in dentistry, and apart from wound care materials (wound dressings, sutures, see Chapter 2 for more details) the number of implanted textile medical devices is quite low and focuses on very few applications, mainly for hernia and blood vessel repair. Table 5.1 gives an overview.

The main advantage of textiles are their mechanical properties, their flexibility and elasticity as well as the possible device designs and structures, e.g. the porosity, which all can be adjusted in a wide range, especially for the replacement or reinforcement of soft tissues. These properties can be achieved by the variation of different parameters: fibres can be produced in different diameters (from about 1 nm up to more than 100 µm) and different shapes (round, trilobal, star-shaped); they can have a specified degradation profile or they can be non-degradable; their strength can be adjusted to the requirements; and special processing like texturing allows a certain elasticity even with non elastic polymers. The textile bonding further influences medically important parameters: a textile structure can have wide open pores like in meshes or braids or can be very dense as in paper-like nonwoven. A knitted structure might be first choice where a high elasticity is required, whereas a woven fabric normally shows nearly no elasticity. Even fibre reinforced materials with high strength and stiffness have been developed for applications in osteosynthesis but only a few found their way to the market. However, polymeric materials are already used in low load bearing areas such as in the upper part of the cranium (e.g. screws and plates made of resorbable Poly-L, D-lactic acid (PLDLA)) or as fusion cages in the spinal cord (Polyether ether ketone (PEEK)) and so it is only a matter of time before more fibre reinforced devices will be used: they are lighter and their elastic modulus can better be

Table 5.1 Major applications for implantable textile medical devices

Application	Implant
Abdominal wall, hernia	Meshes, patches
Blood vessel	Tubular prostheses (woven, knitted, nonwoven), stents, stent graft coatings
Dura	Patches (nonwoven)
Heart	Patches, occluder, suturing ring of valves
Osteosynthesis	Fibre reinforced devices, cords for fixation
Tendon/ligament	Reinforcement
Trachea, oesophagus	Prostheses

© Woodhead Publishing Limited, 2011

adjusted to the bone than metallic devices. It has been demonstrated that the lower modulus of polymeric devices stimulates the bone cells and improves bone healing. Due to this huge variability in properties and structures the use of textile implants will certainly increase in the future.

The use of textiles as implants was encouraged by the development and gross production of synthetic polymers in the middle of the last century. For a long time surgeons and medical device companies used polymers and devices which were easily available from other consumer products and technical applications like polyester (polyethylenterephthalate, PET) and nylon (polyamide, PA) used in garments or polypropylene (PP), used in technical applications. Recent developments have sought to modify or, mainly in the case of resorbable polymers, to synthesise new polymers with properties adjusted to the medical application or with a better biocompatibility. These adjustments concern cellular adhesion (or non-adhesion), degradation profiles, functionality and overall biocompatibility.

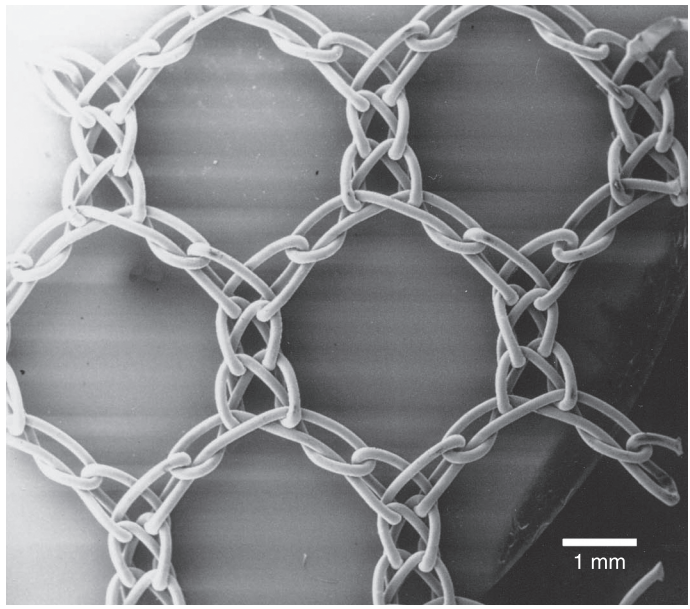
5.2.2 Hernia meshes: application, products, trends

The most frequently used textile implants worldwide are hernia meshes; more than a million are implanted every year. Hernias occur quite often, mainly in the form of organs and tissues penetrating through the abdominal wall, but these protrusions can also occur in other parts of the body. This is not only painful but causes the risk that the penetrating organ, i.e. the gut, is injured. The mechanical stress will at least cause an inflammation. The closure of the defect is important and is one of the most common surgical procedures: more than 1 million operations are performed in the US and more than 250 000 in Germany per year.

Historically, openings were closed by suturing and this is still a common treatment. The 'tension free repair' with meshes is a relatively new therapy, allowing a faster recovery. The first meshes were implanted in the 1950s. These meshes were made of polyethylenterephthalate (PET) multifilament (e.g. Mersilene®, Ethicon Inc.), but in the 1960s polypropylene (PP) monofilaments became available as mesh material; these are still the most relevant materials because it has been shown that PET loses strength over time (>10 years (Riepe *et al*., 1997)). As strength may not be needed over such a long time period, PET meshes are still available.

Most of the meshes are warp knitted, which allows some elasticity and also allows the mesh to be cut to the desired size (Fig. 5.1). Expanded polytetrafluoroethylene (ePTFE) as porous membrane or polyvinylidene fluoride (PVDF, DynaMesh®) are also used as mesh material/patch, because they reduce adhesion, one of the possible complications in hernia reinforcement, but these materials have low elasticity and also do not bind to the tissue, that they should close. This is reflected by a higher rate of recurrence.

© Woodhead Publishing Limited, 2011



5.1 Typical warp knitted structure of a hernia mesh.

Trends

Although meshes for hernia repair are well established devices and are widely used, there are several known problems that can arise after implantation: the formation of scar tissue after inflammation and chronic pain is the most significant (Bay-Nielsen *et al*., 2001). It is therefore not surprising that new materials and devices have been developed to overcome these obstacles. Alongside the non-resorbable meshes, some degradable or partially degradable products arrived on the market, e.g. a polyglycolic acid mesh (DEXON mesh®, Covidien) or a mesh with 50% PGA and 50% PP (Vypro II, Ethicon). Resorbable meshes are supposed to reduce side effects, such as pain or fistula formation.

Because it has been assumed that one major cause of pain is the usage of clips for fixation, self-fixating meshes were developed. Typical examples are the Parietex ProGrip™ mesh, developed by SOFRADIM, France, a low-weight (40 g/m^2) monofilament polypropylene (PP) knitted fabric which incorporates resorbable polylactic acid (PLA) micro hooks (Chastan, 2006; Hollinsky *et al*., 2009). It is also postulated that a higher porosity with a distance of >1 mm between the filaments would result in a reduction of inflammation (Mühl *et al*., 2007). The DynaMesh pp-light® (FEG Textiltechnik) and Optilene® Mesh Elastic (B. Braun) are meshes of this type, with pores from 0.1 to 3.6 mm.

A more recent application is the use of small strips of textile meshes for the treatment of female incontinence. The tension-free transvaginal tape (TVT)

© Woodhead Publishing Limited, 2011

implant is positioned underneath the urethra by a minimal invasive procedure to stabilise it. Cure rates of more than 80% have been reported (Nilsson *et al*., 2008). The size of the mesh has been reduced and the operation procedure optimised (e.g. TVT-secure by Johnson & Johnson and many others).

On the other hand trends for the typical hernia meshes are unclear. Self-fixation is a clear trend whereas other properties are subject to different opinions: resorbable or not, optimal pore size and fibre diameters, the need to avoid adhesion, standard or minimal invasive operation procedure. These points are still under investigation. A new means of modifying meshes is to coat them with titanium by chemical vapour deposition (TiMesh®, pfm medical titanium). Thus the known good biocompatibility of titanium is combined with the mechanical advantages of a textile structure, resulting in a reduced foreign body reaction and a reduction in side effects caused by inflammation. Another interesting aspect which has received less attention would be the creation of the typical elasticity of the abdominal wall.

5.2.3 Vascular prostheses: applications, products, trends

The second most important textile device for implantation is the artificial blood vessel. These devices are mainly inserted into an existing artery. Degenerative changes of the vessel wall are prevalent mainly resulting in arteriosclerosis. This results in thickening, the loss of elasticity and, finally, in stenosis or even occlusion of the vessel. The most frequent case is the stenosis of coronary arteries; for their bypass natural arteries (mainly veins from the leg) are still the first choice. It is known that small diameter coronary prostheses (with diameters ≤ 6 mm) are not effective: the body's reaction to the foreign material will cause an occlusion of the device in a very short time. Several strategies have been developed to overcome this, such as specific textile constructions (Moghe *et al*., 2008), coatings of the device with very hydrophobic surfaces or coagulation-inhibiting substances, but these were not very successful in the coronary area. All the same, prostheses of hydrophobic PTFE are used in the periphery, e.g. as femoral bypass (e.g. Gore-tex® Stretch vascular graft or VascuGraft® PTFE from B. Braun).

Textile prostheses are used where diameters of more than 6 mm are to be replaced. The most common textile prosthesis is used for the abdominal aortic aneurysm (AAA), a bulge of the aorta close to the bifurcation into the two iliac arteries leading into the legs. Other parts of the aorta can also be affected, e.g. the aortic arch. AAA is caused by a dilatation of the weakened vessel wall and occurs most commonly in older men (> 60 years old). The disease is normally symptom-free but may end in a rupture of the aorta which leads to death within minutes due to the internal bleeding (Upchurch *et al*., 2006). It is estimated that, worldwide, 4.5 million people are living with an abdominal aortic aneurysm; in the USA about 15 000 people die per year from the rupture of the AAA. The aneurysm can easily be detected by ultrasound; a repair with a prosthesis is considered, depending on the size of the aneurysm.

© Woodhead Publishing Limited, 2011

History

The idea to use textile vascular prostheses came up in the USA in 1952, when their suitability was demonstrated in animal experiments. Voorhees and his group then replaced an abdominal aneurysm successfully in 17 patients with textile structures sutured to tubular forms (Blakemore and Voorhees, 1954). They used Vinyon, a PVC fibre based (polyvinylchloride) cloth, but PVC is not suitable for long-term implants, because the plasticiser, used to make the fibre flexible, is toxic and leaches out of the material. The polyamide (e.g. nylon) used subsequently is also not suitable, because this polymer degrades over time and causes leakages. Today the most commonly used material is polyethylene terephthalate (PET), thanks to the famous cardiac surgeon Michael DeBakey, who first introduced this material for this application (DeBakey *et al*., 1958). This polymer turned out to be very blood- and biocompatible and is therefore still used today. A slight loss in strength over the years is less relevant in this case than in the above described hernia meshes, but is still a major concern, along with dilatation of the whole prosthesis (Diéval *et al*., 2008). The first PET fibres used were standard materials from DuPont, available under the trade name Dacron® and today these arterial prosthesis are still called 'Dacron prosthesis' by many surgeons, whether the material is from DuPont or not. For developers and manufacturers of devices which are intended to be implanted and to stay in the body for the duration of the patient's life it is important to note that the purchase of raw or processed materials for these purposes is somewhat problematic, because manufacturers are afraid of a possible liability, even if national law in most countries only considers the manufacturer of the final device to be liable.

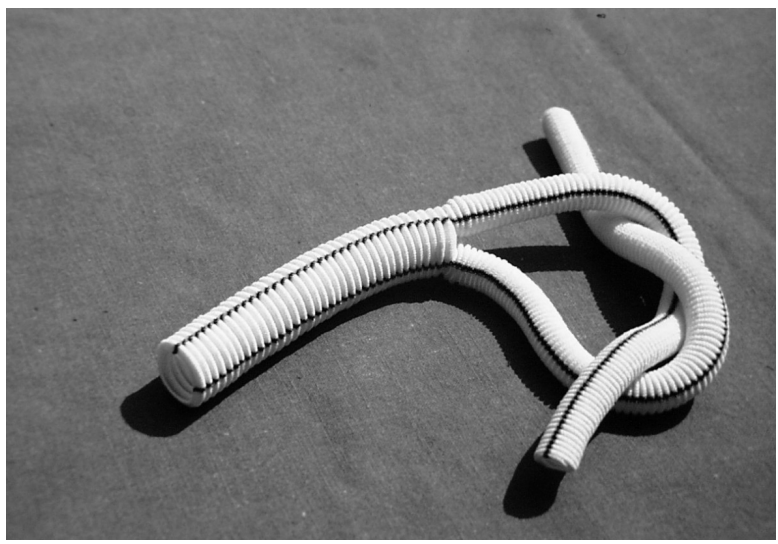
Production process

The prostheses are processed from multifilament yarns by warp knitting or weaving; normal weft knitting is no longer used because of the risk of the knitting unravelling. The first prostheses were woven and were formed and sutured to tubes. Today special machines, based on narrow fabric looms, allow the production of tubular fabrics; a Jacquard loom even allows the direct fabrication of a bifurcation prosthesis. Woven prostheses are very dense and have a low porosity and elasticity but a strong breaking strength; therefore they are mainly used in high-pressure areas like the aortic arc or in patients with a disturbed clotting system. It is important that the ends of the woven tube are fixed in order to avoid the dissolution of the textile structure at the anastomosis (point where the prosthesis is sutured to the native blood vessel). More flexible woven prostheses with a higher porosity can be achieved by using texturised yarns. But most of the prostheses are fabricated by warp knitting. This textile structure is more stable and resistant to unravelling. The elasticity is reduced compared to a weft knit but much higher than in wovens. This is highly recommended because radial elastic

© Woodhead Publishing Limited, 2011

vessel walls actively support the blood transport of the heart by the so-called Windkessel effect. Tubular structures can also directly be produced on double-needle bar Raschel machines, even as bifurcation. This technology also allows the formation of a double velours which makes the material more biocompatible as it promotes the fixation of the prosthesis by penetration of fibroblasts from the surrounding tissue as well as better fixation of the neointima inside (Guidoin *et al*., 1983). Furthermore, as in woven devices, it is possible to integrate a black band of yarn as a guide-line, preventing the twisting of the prosthesis at the time of implantation. In the next step any finish, e.g. used for fibre spinning, has to be removed by solvent extraction. The porosity of the warp knitted structure is reduced with boiling water by using highly shrinkable yarns. The radial stability of the prosthesis is finally fixed by pleating it on a waved rod under heat giving the final shape of the device (Fig. 5.2).

The porosity of the textile structure would cause the problem of bleeding if these pores are not temporarily closed. This used to be achieved by soaking the artificial vessel in blood and allowing it to clot. Today most prostheses are coated with a gel, usually gelatine. In both cases the closing material is degraded over time by the body and replaced by proteins deposited from the blood which is called neointima or pseudointima. The pleated structure will cause turbulences in the blood stream which also promotes deposition. Unfortunately, artificial blood vessels are not reseeded by endothelial cells: the natural lining of vessels, known as intima, avoids thrombus formation and sclerosis. Only approximately 1 cm from anastomosis is reseeded with these cells.



5.2 Typical warp knitted PET bifurcation vascular prosthesis.

© Woodhead Publishing Limited, 2011

Trends

Vascular prostheses have demonstrated a good compliance over the last 50 years but the operation procedure involves some risk of failure and death of the patient, which increases with the length of the aneurysm, the morbidity of the original vessel and the inclusion of the renal arteries in the aneurysm (overview in Tallarita *et al*., 2011). Therefore alternatives are under development, the most promising and advanced of which is known as the stent-graft, which was developed in the mid to late 1990s. The typical stent is a metallic tubular grid or braid made of steel or nitinol (a shape-memory alloy of titanium and nickel), and is generally expanded into blocked coronary arteries to keep them open. If the open structure of a stent is coated it is called a stent-graft. In an abdominal aortic aneurysm stent-grafts were developed to avoid the opening of the abdomen. A stent-graft can be introduced percutaneously by minimal invasive techniques through the femoral arteries by using catheters, a process called endovascular aneurysm repair (EVAR; Greenhalgh and Powell, 2008). Grafts are also available for the thoracic aortic aneurysm, but then the access is from the side of the chest. The two branches of a bifurcation are usually introduced separately from both legs and combined inside the artery. The stent-graft serves as an artificial artery avoiding the risk of rupture of the aneurysm. The coating replaces the wall of the artery. It can be a polymer film, a membrane or a textile. Gore, for example, uses its expanded PTFE, which already is in use for small diameter blood vessel prostheses; a version which has additionally been activated with heparin has also recently been developed (GORE®VIABAHN® endoprosthesis with PROPATEN bioactive surface). C.R. Bard (Flair™) also uses PTFE for their stent-graft, whereas Medtronic (Valiant™), Cook (Zenith®), Lombard Medical (Aorfix®), Jotec (E®-vita) and others use PET textile structures for coating the stent. The EVAR is not yet possible if major side vessels like the renal arteries are included in the aneurysm.

Another attempt to make vascular prostheses more blood compatible is the seeding of the inner surface of the prosthesis with endothelial cells to reconstitute the natural inner lining of the blood vessels (Seifalian *et al*., 2002; Büttemeyer *et al*., 2003). These cells prevent coagulation and the formation of a thrombus but it seems to be difficult to hold these cells on the artificial surface for longer time periods. One quite new method avoids a preseeding of the prosthesis but tries to attract pre-endothelial cells from the blood stream (Avci-Adali *et al*., 2008). New developments also try to suppress bacterial growth, because intra-operative infections are still a general problem causing persistent biofilms on implants. Maquet (Intergard Silver®) as well as B. Braun (Silver Graft®) have introduced vascular prostheses into the market, which are coated with silver to reduce bacterial survival. When regenerative medicine began to show potential (Section 5.3) interesting experiments were performed to grow complete blood vessels in a laboratory reactor (L'Heureux *et al*., 1993), but these re-grown vessels have reached the patient only in a few clinical studies.

© Woodhead Publishing Limited, 2011

Other blood-contacting devices

Less important when compared to AAA prostheses are other applications of textile materials for blood contacting implantation: nonwoven patches are usually used in a procedure known as an endarterectomy to prevent a stroke, when a carotid artery is blocked with a plaque, but the operation is also very risky. The warp knitted PET that is used for the vascular prostheses is also used in mechanical heart valves, as is ePTFE occasionally. It covers the annular frame of the valve and is needed to fix the valve in place by suturing the textile structure to the surrounding tissue. A heart valve completely based on textile structures is under development in several groups worldwide either for percutaneous implantation (Heim *et al*., 2010) or tissue engineering (see Section 5.3.6). Furthermore there have been several attempts to replace metallic stents by resorbable braided fibres. The first resorbable stent on the market (since 2007) is the Igaki-Tamai® stent, made by the Japanese Kyoto Medical Planning Company. It is made of slowly degrading polylactid acid (PLLA), to allow the stent to be integrated into the vessel wall before it degrades. This avoids embolism caused by degraded fragments of the stent. In the periphery porous warped meshes are also used to reinforce transplanted blood vessels (e.g. ProVena® , B. Braun).

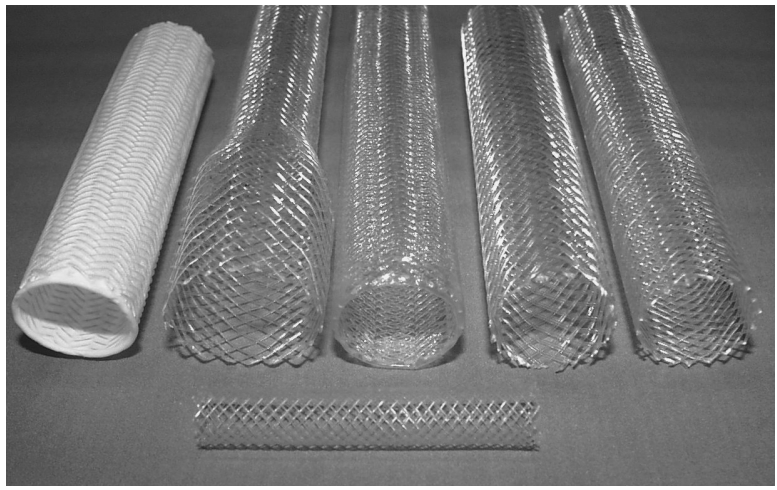
5.2.4 Others

There is a wide variety of other applications for implantable textiles but none has yet proved as important as hernia meshes or vascular prostheses. Nonwovens are used as patches in different organs: they replace the dura mater, for example, which is the outmost membrane enveloping the brain. In neurosurgical procedures dural substitutes are used to avoid leakage of brain fluids and to allow healing after the surgery. Natural duras from pathology or animal origin are still used (Durepair®, Medtronic or Lyoplant®, B. Braun), but may in rare cases cause infections and so a synthetic material is preferred today, like Neuro-Patch® from B. Braun, made of purified polyesterurethane. Nonwovens are also used as pledgets to support medical sutures in delicate and weak tissues and can be non-resorbable (e.g. PTFE) or resorbable (e.g. polyglactin 910).

Stents are not only used to stabilise blood vessels, but are also used for most tubular organs to keep them open after injury or surgery. In all these therapies polymeric resorbable and non-resorbable braided monofilaments are used. Typical applications are the laryngeal and tracheal stents like the Polyflex® oesophageal and airway stents (Boston Scientific), biliary and enteral stents. In the authors' laboratory resorbable stents for these applications have successfully been developed (Wolters *et al*., 2010; Fig. 5.3).

Last not but not least, in the economically important field of osteosynthesis and tendon repair, resorbable braided cords or narrow woven fabrics, e.g. made of polydioxanone (PDO), are occasionally used to fix bones in a defined position or to reinforce tendons or ligaments for the process of healing.

© Woodhead Publishing Limited, 2011



5.3 Resorbable stents for biliary and enteral applications.

5.2.5 Regulatory aspects

Textile based implants are medical devices whose use is subject to regulation worldwide: before bringing these devices to the market they have to be approved by various bodies, in the United States by the FDA and in Europe by a notified body. The regulations differ slightly between countries and may also be dependent on the intended use, which has to be exactly defined. At the very least the safety and functionality of the device has to be proven but clinical studies need not be as extensive as for pharmaceuticals. However, to get the certification a complete documentation has to be filed to the regulatory agency, which has to include the intended field of application, a history of the development, a risk analysis, a documentation of the quality management, the specifications of the device and how they are followed and guaranteed, the results of the testing *in vitro* and *in vivo*, clinical data and if applicable also a comparison with similar existing devices. The necessary quality management should be in accordance with ISO 13485, a standard which assigned the general ISO 9000 quality management standards to medical device manufacturers (ISO 13485, 2003). The current version describes quality management in terms of processes with distinct responsibilities. One important process is the development of new devices. Hence it is recommended that this standard should be considered right at the beginning of the product development so that everything needed for the approval of the medical device is documented.

Functionalised medical devices might be considered differently, for example if they deliver drugs or if they are seeded with cells. In these cases it will be much more difficult to achieve the certification, if the device is considered for example as a combination product or a pharmaceutical.

© Woodhead Publishing Limited, 2011

5.3 Textiles for regenerative medicine

5.3.1 Overview of regenerative medicine

Regenerative medicine is one of the most promising research areas in medical sciences: while today the function of damaged tissues or organs is recovered with artificial devices, the aim is that these tissues will be repaired in the future by inducing and/or guiding regenerative processes to restore or establish normal function. The primary idea of using resorbable filaments as carriers to grow cells outside the body and to re-transplant them into the body were developed at the Massachusetts Institute of Technology (Vacanti *et al*., 1988; Mikos *et al*., 1993; Langer and Vacanti, 1993) and was called 'tissue engineering'. Despite concerted efforts worldwide within the last 20 years, which have applied the technology to nearly every organ or tissue, the outcome has so far been disappointing. The complex regulation of living tissue is fairly well understood and thus a major problem remains the integration and connection of the 'engineered' tissue into the existing environment in the body. Therefore the approach was broadened under the term of 'regenerative medicine'. Most of today's procedures try to guide regeneration inside the body rather than to build up the whole tissue in the laboratory. For this approach cells are not necessarily needed: depending on the tissue to be regenerated, biomaterials, cells and/or signalling molecules (mediators) might be used in different combinations. It is therefore difficult to define which therapeutic approach can be called regenerative medicine. In a recent publication the number of 323 000 patients was calculated for the time period 1988–2010, limited to those treated with cell-based therapies approved by FDA or EMA (Mason and Manzotti, 2010). Considering all therapies which can be summarised under the term regenerative medicine the figure will stretch to millions of patients.

5.3.2 Materials, structures, cells and mediators

Materials and structures

When scientists started to 'engineer' three-dimensional tissues for transplantation they used nonwovens made of resorbable sutures, mainly PGA (polyglycolic acid) and PLGA (Polyglactin 910, a copolymer of 90% polyglycolic acid and 10% lactic acid). The suture material was available and was approved for use in medical applications. The fibres had the necessary strength and degraded quite quickly. This was important, because it was expected that the cells would produce their own matrix in a short time and the carrier material should degrade by the time the new matrix is formed.

Meanwhile a broad variety of materials is used. The degradation time is ideally adjusted to the tissue/function: in cartilage repair short times may be more appropriate whereas in bone the biomaterials should last for more than six months and in a liver support system no degradation may be needed at all. Also of interest

© Woodhead Publishing Limited, 2011

is the macro- and microstructure of the material. The porosity of the whole device can be crucial: in cartilage a single cell in a pore can produce matrix, whereas in a bioartificial liver the cells must have the ability to strongly bind to one another and to form clusters, which requires high porosity. Cells can be entrapped in large pores or on the surface of materials like membranes, fibres or beads. Different technologies are available to form pores in scaffolds adjusted for tissue engineering (Mikos and Temenoff, 2000). On the other hand cells primarily recognise much smaller structures in the range of 1 µm or less. Furthermore the physicochemical properties of the surfaces are also relevant. Most of the synthetic polymers used for fibre production are more or less hydrophobic, whereas cells prefer hydrophilic surfaces, because they do not bind directly to these materials but first deposit matrix proteins like collagen on the material surface. These proteins might be modified or denaturated by a strongly hydrophobic surface. Different strategies have been adopted to overcome these problems, e.g. by coating with hydrophilic components or even covalently binding signalling molecules of the matrix. It should be noted in this context that tissues are very dynamic. A hydrophilic surface allows a reversible attachment of matrices and cells thus supporting normal tissue formation. Therefore more and more natural materials are considered for tissue engineering such as protein-based (collagen, fibrin) or carbohydrate-based (alginate, chitosan, etc) gels. The choice is mainly dependent on the intended tissue/organ. Therefore for every application a very specific material must be designed. In recent years special polymers have been developed, trying to meet the needs of the regenerating tissue. Table 5.2 gives an overview of the

Table 5.2 Biomaterial structures used in regenerative medicine

Structure, processing	Application	Polymers
Gels (hydrogels)	Matrix simulation, glues, drug delivery, haemostyptica, dressings, implant	Collagen, gelatine, alginate, hyaluronic acid, fibrin, agarose, silicone, PEG, PVA, pHEMA
Microspheres, beads	High cell density suspension (spinner culture), cryopreservation	Polystyrol, glass, dextrane, collagen
Foils, membranes, foams	Cell carrier, tissue separation (bone, skin), wound care	PS, PP, PMMA, PSU, PUR, PTFE, PLA, HA, hyaluronic acid, silicone
Capillary membranes	Dialysis, plasma separation, immunoisolation	Cellulose, PSU, silicone, PAN, PLA
Nonwoven	Haemostyptica, cell carrier, dressings	PUR, PES, fibrin, PLA and other resorbable polymers
Other textiles (braided, woven, knitted)	Vascular and ligament prosthesis, hernia	PET, PTFE, PGA, PLA, PP, and others

© Woodhead Publishing Limited, 2011

structures used in tissue engineering, their possible area of application and the polymers used to create them.

Cells

In tissue engineering specific cells had been isolated from the patient's body, proliferated in the laboratory, seeded into scaffolds and then brought back into the injured tissue. Whereas some cells can be multiplied in culture (e.g. fibroblasts and keratinocytes from the skin) most of the cells are highly differentiated and failed to be propagated *in vitro* (e.g. hepatocytes from liver, chondrocytes from cartilage). In these cases different strategies were developed: some cells can be proliferated after dedifferentiation (as in cartilage), xenogenic cells might be used (as in liver or pancreas) or, quite recently the use of stem cells has been considered. It is possible to harvest autologous stem cells, allow them to proliferate and then differentiate them into the desired cell type, but not all differentiation processes are sufficiently understood. It is also possible to attract these cells by signalling molecules as has been described for blood vessels (Avci-Adali *et al*., 2008). However, many approaches in regenerative medicine do not use isolated cells but try to stimulate and to control the process of regeneration in the body with specific materials and signalling molecules.

Signalling molecules

More and more molecules are being identified which help cells to communicate with each other; these are often called mediators or cytokines. Growth factors stimulate proliferation (such as EGF, the epidermal growth factor; NGF, the nerve growth factor; FGF, the fibroblast growth factor; and IGF, the insulin-like growth factor). These factors are also responsible for the differentiation into highly specific cells. FGF and IGF as well as the TGF- superfamily (transforming growth factors), for example, are involved in the differentiation of stem cells into chondrocytes. A crucial subject in regeneration is angiogenesis, because newly formed tissues have to be connected to the blood stream. FGF, as well as VEGF (vascular endothelial growth factor) are important factors in the stimulation of vessel growth. Even some gases have signalling functions, such as nitric oxide and carbon monoxide. It is a major challenge of regenerative medicine to include these signalling molecules in devices and to deliver them at the right moment at the intended location.

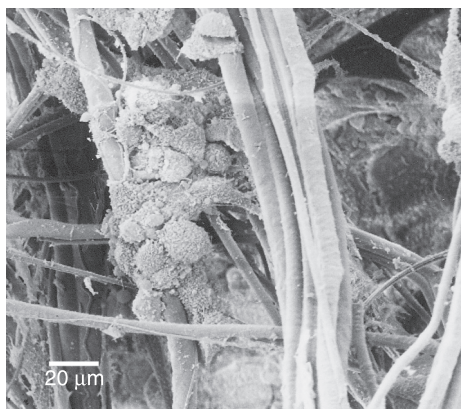
5.3.3 Cartilage: closing three-dimensional defects

Cartilage is a tissue consisting of collagen, mainly type II and GAGs (glucosoaminoglycans), which is not connected to the blood stream and is aneural. Nutrients and oxygen come only by diffusion from surrounding fluids like the

© Woodhead Publishing Limited, 2011

synovium in joints. It comprises mainly water (about 70%) and a very small amount of chondrocytes producing this matrix. Three types of cartilage are distinguished: elastic cartilage (with additional elastin, e.g. in the auricle, part of the ear), hyaline cartilage (mainly articular cartilage, covering bones, but also in the larynx, trachea, and bronchi) and fibrocartilage (also containing fibrous tissue and found mainly in the annulus of intervertebral discs). In the case of injury or degeneration, cartilage has a very low ability to regenerate. The most interesting area from a therapeutic view point is joints, mainly the knee: an estimated number of 27 million Americans are said to be affected by cartilage degeneration due to osteoarthritis. If joints fail they are normally replaced by artificial devices: 2 million knees and hips will probably be replaced in the year 2015 in the USA alone.

Today chondrocytes can easily be isolated from biopsies and proliferated in a laboratory. At this stage cells are dedifferentiated into fibroblasts and produce a different matrix, mainly consisting of collagen I, which is not suitable for larger defects in joints. Thus it is the challenge of tissue engineering concepts to redifferentiate these cells to chondrocytes and to maintain this status as long as possible after transplantation of the cells. To achieve this goal and to seed the cells in the three-dimensional form of the defect to be regenerated, different matrix materials have been developed in the past. One of the first ideas in tissue engineering was to use resorbable nonwoven materials for this purpose (Langer and Vacanti, 1993). The degradation profile of the materials has to be consistent with the formation of a new matrix by the chondrocytes. Because cells form their matrix very quickly, in many laboratories polyglycolic acid (PGA) was used which degrades within a few weeks. From melt spun PGA fibres nonwoven disks with a porosity of about 97% and a thickness of 2.5 mm were produced in the authors' laboratory, seeded with porcine chondrocytes in multi-well plates and incubated under cell culture conditions up to ten weeks. Figure 5.4 demonstrates



5.4 Chondrocytes in a PGA scaffold.

© Woodhead Publishing Limited, 2011

that cells keep their round shape in these nonwoven scaffolds, which is typical for differentiated chondrocytes. Results with these scaffolds are contradictory: some laboratories had problems achieving the typical cartilage-like matrix and changed to gel-based matrices, but these materials have the disadvantage of a lower stability and resistance. On the other hand there are products based on nonwovens on the market, which claim to have had successful results in many patients (e.g. BioSeed®-C from BioTissue). In the future both matrices may be combined.

5.3.4 Nerves: guided tissue regeneration

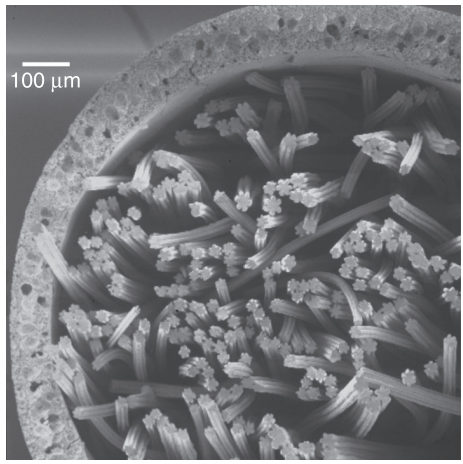
Peripheral nerves fail to regenerate greater gaps after lesion/trauma. In contrast to other tissues a cut nerve can not reconnect; a nerve controlling a finger, for example, has to re-grow out from the cut to the target muscle. The formation of scar tissue and missing guiding structures hinder the outgrowing axon. Therefore autologous nerve grafts are generally used in this case with limited success and morbidity at the donor site. Nerve guide tubes (e.g. NeuraGen®, a collagen tube from Integra; Neurolac® a caprolacton–DL-lactide copolymer from Polyganics; Hydrosheath™, a PVA gel from Arthrex; and NeuroTube™, a woven PGA tube from Synovis Micro Companies Alliance) are alternatives. A recent overview of published data on about 300 patients (Schlosshauer *et al*., 2007) summarises that non-resorbable devices often fail due to late compression symptoms whereas resorbable devices give better results. Acidic degradation products from synthetic polymers may cause irritation affecting the newly formed nerve, whereas the degradation of collagen cannot easily be adjusted. To avoid these problems a block-copolymer from trimethylene carbonate and ε-caprolactone was developed by our group. Hollow fibre membranes (nerve guide tubes) of 1 mm diameter were formed from these polymers via the phase inversion technique. These tubular resorbable nerve guides, seeded with Schwann cells, were able to regenerate nerves even across larger gaps of 2 cm *in vivo* (Sinis *et al*., 2005).

In nature, Schwann cells (SCs) reorganise to form longitudinal Büngner bands which function as guides for re-growing axons. In our group these bands were simulated by filaments with longitudinal grooves, which were produced by melt-spinning with a star-shaped nozzle. These filaments were integrated into the nerve tubes described above (Fig. 5.5); they showed good biocompatibility and also oriented attachment of Schwann cells (Ribeiro-Resende *et al*., 2009). Good results were also achieved with silk fibres. Isolated filaments therefore seem to be a good material for guided tissue regeneration. Even PGA nonwovens, seeded with stem cells, have been used for the regeneration of the spinal cord (Vacanti *et al*., 2001).

5.3.5 Liver: metabolic active biohybrid organs

The best therapy for people suffering from acute liver failure would be transplantation but due to the shortage of donor organs most of them cannot be transplanted within

© Woodhead Publishing Limited, 2011



5.5 Tubular nerve guide with integrated fibres with microgrooves.

reasonable time. It is therefore not surprising that among the first cells which were transplanted in a fibrous scaffold into animals were hepatocytes (Vacanti *et al.*, 1988). Today it is generally agreed that bioartificial liver support systems (BALs) would be sufficient for these patients: they temporarily detoxify a patient's blood until the liver is regenerated or until a transplantable organ becomes available. Several concepts have been developed in the past: the highest number of patients was treated by Demetriou in Los Angeles (Demetriou *et al.*, 2004) with limited success. He seeded hepatocytes on the surface of beads to enable better storage (cryopreservation) and filled these beads in a BAL. The patients' plasma is then pumped through a charcoal column and an oxygenator and finally through a BAL where plasma and cells are separated by hollow fibre membranes. A major obstacle is the cell source: human hepatocytes do not proliferate *in vitro*. Demetriou initially used porcine cells from animals he bred on a special farm for safety reasons (to avoid the transfection with animal diseases). But porcine metabolic activity is different from human liver activity and it is not possible to completely protect porcine hepatocytes from immune rejection. Thus today research focuses on the use of adult human stem cells. In the BAL developed in our laboratory, based on a melt-blown nonwoven made of polyurethane fibres (Linti *et al.*, 2002), there were promising results in terms of differentiating stem cells into liver cells by co-cultivating stem cells with hepatocytes. Actually it seems that resorbable nonwovens can offer a good stem cell niche, where these cells can differentiate (Li *et al.*, 2010).

5.3.6 Others

There is almost no organ or tissue that has not been considered for regenerative therapies. Economically the treatment of injured/fractured bone is by far the most

© Woodhead Publishing Limited, 2011

important surgical activity, but nearly no textile structures are used in this field. This is due to the high load that bone is exposed to: it is thus not surprising that most of the materials used in osteosynthesis are metals and sometimes ceramics. There are nevertheless some areas where textile devices are applicable: fibre reinforced devices and regeneration of large bone defects. For example, orthopaedic implants made from carbon fibre reinforced PEEK, produced by Icotec in a process called composite flow moulding (CFM), have fairly recently been introduced. The use of fibrous materials for the regeneration of large bone defects is still under development. Compared to the foams and ceramics that are normally used, textile structures may allow larger pores and thus the ingrowth of blood vessels but may lack the necessary strength.

Textile structures, mainly nonwoven, seem to be a suitable scaffold for any type of cell, but porosity, stiffness and degradation profiles have to be adjusted for each organ. Among these tissues and aside from those already described, blood vessel regeneration may be the most relevant for textile structures. As mentioned before there were promising experiments to grow a complete blood vessel in a lab reactor (L'Heureux *et al*., 1993): this technology has been improved using only cultured fibroblast sheets to form small diameter blood vessels. The US company Cytograft Tissue Engineering is trying to bring this technology to the market, and the first patients have already been successfully treated. Interesting results were achieved with nonwovens produced by electrospinning (see also Chapter 4): this process forms very fine fibres in the nanometre range which are not only suitable in fibrous tissues (Mauck *et al*., 2009), but may also be suitable to be seeded with endothelial cells thus forming the typical elastic membrane these cells are growing on in nature. Surface modifications allow cell attachment even on originally hydrophobic surfaces and simulate natural matrices like the RGD-peptide, a small sequence of three amino acids (arginine, glycine and aspartic acid) in the matrix protein fibronectine, which is recognised by cells for attachment.

5.3.7 Regulatory aspects

The regulation of regenerative therapies is more complex than for implants. Depending on the process to be approved it may be a medical device (e.g. a wound dressing material that supports the regeneration of skin), a pharmaceutical (e.g. a bone morphogenetic protein), a cell therapy (e.g. chondroctyes transplanted into the knee) or a combination product. National agencies had some problems in devising regulations for this relatively new type of therapy: it was not until 2007 that therapies based on genes or living cells or tissues were classified in Europe as advanced therapy medicinal products (ATMPs). These products will be handled like pharmaceuticals and approved by the EMA (European Medicines Agency). This results in a strong regulation not only on the production side but also at the location of application, e.g. the clinic. In the United States these kinds of products are regulated differently: they have their own department, the Center for Biologics

© Woodhead Publishing Limited, 2011

Evaluation and Research (CBER), which regulates human cells, tissues, and cellular and tissue-based products (HCT/P) and even gene-therapies. Cells in scaffolds are classified as combination products and may be classed either as biologics or as medical devices.

5.3.8 Trends in regenerative medicine

In the beginning, when the idea of regeneration was realised as 'tissue engineering', research was dominated by the opinion that cells have to be isolated and processed in the laboratory and then 'transplanted' into the body like a transplantable organ. After more than 20 years of experience it seems that a better approach is to stimulate and guide the regeneration inside the patient. This sounds easier than processing cells and controlling their differentiation but in reality it is even more complex, because the signals, molecules and processes of regeneration in living tissues are yet only partially understood. Thus today regenerative medicine is much more than transplanting cells in a scaffold. Signalling molecules, biomaterials and cells will be used alone or in various combinations. We need to learn which signal is needed at which time point and how it can be delivered at precisely this moment; we will have to develop new biomaterials which ideally can be degraded by the hosting tissue at a time when new tissue has formed and where the degradation products can be used or at least metabolised by the cells. We will also have to learn more about stem cells, their differentiation and signals involved in this process, so that these cells can be attracted to the tissue to be regenerated, a process called homing. Another challenge of the future is the interface between different organs or tissues, e.g. bone – cartilage or bone – tendon, which has to be addressed (Yang and Temenoff, 2009). All this knowledge will not provide us with a common solution for the problems: in the future every tissue or organ will still need a unique regeneration therapy and there will still be areas where cells will be processed in a lab, like bridging hepatic failures with a BAL.

5.4 Testing of implants and materials for regenerative medicine

It is part of any regulation that new devices and therapies are extensively tested *in vitro* and *in vivo* to prove their functionality and safety. *In vitro* testing of medical devices like textile implants include a broad number of chemical, mechanical and biological tests. For most of these tests standards have been developed. Horizontal standards considering more general aspects of testing a class of products are distinguished from vertical standards describing detailed test protocols and requirements for a single product. The horizontal standard series ISO 10 993, 'Biological Evaluation of Medical Devices' summarises all relevant *in vitro* test methods for medical devices such as textile implants. Part one gives an overview

© Woodhead Publishing Limited, 2011

and guidelines on which test might be appropriate for which device. Other parts deal with blood compatibility, cytotoxicity, irritation and sensitisation effects, genotoxicity, degradation products, sterilisation, toxicokinetics, and chemical characterisation. A standard for tissue engineered products containing living cells is under development (ISO 13 022, 'Medical products containing viable human cells – Application of risk management and requirements for processing practices').

For a specific device a large number of vertical standards exist, e.g. ISO 25 539 on 'Cardiovascular implants – Endovascular devices'; ISO 7198 on 'Cardiovascular implants – Tubular vascular prostheses'; or ISO 22 442 on 'Medical devices utilising animal tissues and their derivatives'. For tissue engineered medical products more than 20 standards were developed at ASTM (American Society for Testing and Materials), e.g. F2451-05 'Standard Guide for *in vivo* Assessment of Implantable Devices Intended to Repair or Regenerate Articular Cartilage'. Finally, standards for clinical studies also exist, such as ISO 14 155 'Clinical investigation of medical devices for human subjects'.

5.5 Sources for further information

Further information can be obtained from many sources. Current products are exhibited at trade fairs (the largest of these is 'medica' in Dusseldorf, http://www.medica-tradefair.com/), but many companies have exhibitions at major conferences of surgeons. In most countries societies or colleges of surgeons will hold annual conferences addressing current developments and problems. A more distinct view on future developments of the subjects described in this chapter is given at the biomaterials societies (an overview of all relevant societies can be found at the International Union of Societies for Biomaterials Science and Engineering (IUSBSE), www.worldbiomaterials.org) and at the 'Tissue Engineering and Regenerative Medicine International Society' (TERMIS®, www.termis.org) with European, American and Asian chapters. Both groups of societies organise conferences every year in every continent and sometimes world congresses, which will give a good overview of current developments. Interesting articles and reviews may be found in many international journals, like *Journal of Materials Science – Materials in Medicine* or *Journal of Biomedical Materials Research* for implants, and *Tissue Engineering* for regenerative medicine as well as *Biomaterials* for both subjects.

5.6 References

Avci-Adali M *et al*. (2008). 'New strategies for in vivo tissue engineering by mimicry of homing factors for self-endothelialisation of blood contacting materials', *Biomaterials*, 29(29), 3936–3945.

Bay-Nielsen M *et al*. (2001). 'Danish Hernia Database. Pain and functional impairment 1 year after inguinal herniorrhaphy: A nationwide questionnaire study', *Ann Surg*, 233, 1–7.

© Woodhead Publishing Limited, 2011

Blakemore A H, Voorhees A B Jr (1954). 'The use of tubes constructed from vinyon N cloth in bridging arterial defects; experimental and clinical', *Ann Surg*, 140(3), 324–334.

Büttemeyer R *et al.* (2003). 'In a pig model ePTFE grafts will sustain for 6 weeks a confluent endothelial cell layer formed in vitro under shear stress conditions', *Eur J Vasc Endovasc Surg*, 26(2), 156–160.

Chastan P (2006). 'Tension free open inguinal hernia repair using an innovative self gripping semi-resorbable mesh', *J Min Access Surg*, 3, 139–143.

DeBakey M E *et al.* (1958). 'Clinical application of a new flexible knitted Dacron arterial substitute', *Am Surg*, 24(12), 862–869.

Demetriou A A *et al.* (2004). 'Prospective, randomized, multicenter, controlled trial of a bioartificial liver in treating acute liver failure', *Ann Surg*, 239(5), 660–667, discussion 667–670.

Diéval F, Mathieu D, Durand B (2008). 'Influence of textile structure on longitudinal ruptures' localisation of the vascular prostheses', *Textile Res J*, 78(5), 427–438.

Greenhalgh R M, Powell J T (2008). 'Endovascular repair of abdominal aortic aneurysm', *N Engl J Med*, 358(5), 494–501.

Guidoin R *et al.* (1983). 'Polyester prostheses as substitutes in the thoracic aorta of dogs. I. Evaluation of Commercial prostheses', *J Biomed Mater Res*, 17, 1049–1077.

Heim F, Durand B, Chakfe N (2010). 'Textile for heart valve prostheses: fabric long-term durability testing', *J Biomed Mater Res B: Appl Biomater*, 92(1), 68–77.

Hollinsky C *et al.* (2009). 'Comparison of a new self-gripping mesh with other fixation methods for laparoscopic hernia repair in a rat model', *J Am Coll Surg*, 6, 1107–1114.

ISO 13485 (2003). 'Medical devices – Quality management systems – Requirements for regulatory purposes', 2nd edition (www.iso.org).

L'Heureux N, Germain L, Labbé R, Auger F A (1993). 'In vitro construction of a human blood vessel from cultured vascular cells: a morphologic study', *J Vasc Surg*, 17(3), 499–509.

Langer R, Vacanti J P (1993). 'Tissue engineering', *Science*, 260(5110), 920–926.

Li J *et al.* (2010). '3D PLGA scaffolds improve differentiation and function of bone marrow mesenchymal stem cell-derived hepatocytes', *Stem Cells Dev*, 19(9), 1427–1436.

Linti C *et al.* (2002). 'Cultivation of porcine hepatocytes in polyurethane nonwovens as part of a biohybrid liver support system', *Int J Artif Organs*, 25(10), 994–1000.

Mason C, Manzotti E (2010). 'Regenerative medicine cell therapies: numbers of units manufactured and patients treated between 1988 and 2010', *Regen Med*, 5(3), 307–313.

Mauck R L *et al.* (2009). 'Engineering on the straight and narrow: the mechanics of nanofibrous assemblies for fiber-reinforced tissue regeneration', *Tissue Eng Part B Rev*, 15(2), 171–193.

Mikos A G *et al.* (1993). 'Preparation of poly(glycolicacid) bonded fiber structures for cell attachment and transplantation', *J Biomed Mater Res*, 27, 183–189.

Mikos A G, Temenoff J S (2000). 'Formation of highly porous biodegradable scaffolds for tissue engineering', *Elec J Biotechnol*, 3(2), 1–6, Available: http://www.ejb.org/content/vol3/issue2/full/5.

Moghe A K, Gupta B S (2008). ' Small-diameter blood vessels by weaving: Prototyping and modelling', *J Text Inst,* 99(5), 467–477.

Mühl T *et al.* (2008). 'New objective measurement to characterize the porosity of textile implants', *J Biomed Mater Res B: Appl. Biomater*, 3, 1–8.

Nilsson C G *et al.* (2008). 'Eleven years prospective follow-up of the tension-free vaginal tape procedure for treatment of stress urinary incontinence', *Int Urogynecol J*, 19, 1043–1047.

© Woodhead Publishing Limited, 2011

Ribeiro-Resende VT *et al*. (2009). 'Strategies for inducing the formation of bands of Büngner in peripheral nerve regeneration', *Biomaterials*, 30(29), 5251–5259.

Riepe G *et al*. (1997). 'Long-term in vivo alterations of polyester vascular grafts in humans', *Eur J Vasc Endovasc Surg*, 13, 540–548.

Schlosshauer B *et al*. (2007). 'Synthetic nerve guide implants in humans: a comprehensive survey', *Neurosurgery*, 59(4), 740–747, discussion 747–748.

Seifalian A M *et al*. (2002). 'Improving the clinical patency of prosthetic vascular and coronary bypass grafts: the role of seeding and tissue engineering', *Artif Organs*, 26(4), 307–320.

Sinis N *et al*. (2005). 'Nerve regeneration across a 2-cm gap in the rat median nerve using a resorbable nerve conduit filled with Schwann cells', *J Neurosurg*, 103, 1067–1076.

Tallarita T, Sobreira M L, Oderich G S (2011). 'Results of open pararenal abdominal aortic aneurysm repair: tabular review of the literature', *Ann Vasc Surg*, 25(1), 143–149.

Upchurch G R, Schaub T A (2006). 'Abdominal aortic aneurysm', *Am Fam Physician*, 73(7), 1198–1204.

Vacanti J P *et al*. (1988). 'Selective cell transplantation using bioabsorbable artificial polymers as matrices', *J Pediatr Surg*, 23(1), 3–9.

Vacanti M P *et al*. (2001). 'Tissue-engineered spinal cord', *Transpl Proc*, 33, 592–598.

Wolters H H *et al*. (2010). 'A new technique for ureteral defect lesion reconstruction using an autologous vein graft and a biodegradable endoluminal stent', *J Urol*, 184(3), 1197–1203.

Yang P J, Temenoff J S (2009). 'Engineering orthopedic tissue interfaces', *Tissue Eng*, 15(2), 127–141.

© Woodhead Publishing Limited, 2011

6

Textiles with cosmetic effects

R. MATHIS and A. MEHLING, BASF Personal Care and Nutrition GmbH, Germany

Abstract: Textiles are an important interface between human beings and the surrounding world. The merging of cosmetics and textiles, cosmetotextiles, offers a unique platform for the delivery of cosmetic products. Bringing perceivable cosmetic performance to textiles is challenging. This chapter gives an overview of the technologies used to encapsulate the ingredients and to apply them to textiles. Examples of some cosmetic functionalities and how to assess their performance are given. A short description of a few guidelines and legal aspects that shape regulatory framework is also given. Cosmetotextiles can convey perceivable and measurable effects which should increase their attractiveness in the future.

Key words: claim substantiation, controlled release, cosmetotextiles, encapsulation.

6.1 Introduction

Clothing has several functions from primarily being used for protection against the environmental influences to being central to style and fashion. Clothing and fashion are both a means of portraying and judging an individual's personality, hobbies, religion and/or occupation. Textiles are pivotal in functioning as our 'second skin' and the main function of textiles is still to help to protect us against environmental assults, e.g. UV radiation or cold. Types and function of textiles are continuously evolving and today, modern finishes can add a new element to textile function. The merging of cosmetics and textiles offers a unique platform for the delivery of cosmetic products, such as moisturisers, or sensorial active ingredients, such as cooling agents, during wear. The increased convenience coupled with functionality converts cosmetotextiles into true 'active' players to increase our sense of wellbeing. The name 'cosmetotextiles' has been coined to designate textiles with cosmetic properties, but these types of textiles can also harbour other actions or functions, such as medical properties, mosquito repellents, odour reducers, antimicrobials or UV-protection agents.

Although most people are familiar with the concept of impregnated textiles when used as a disposable wipe, the idea of loading our daily garments with cosmetics is relatively recent. Developing cosmetotextiles poses various technical challenges as the cosmetic ingredients need to be evenly distributed and invisibly incorporated into the fabric in such a way that effective skin care takes place while as little as possible is lost during laundering. The main technology used for this targeted controlled release is microencapsulation.

© Woodhead Publishing Limited, 2011

This chapter focuses on technologies, functions, methods to prove the efficacy of cosmetotextiles and some of the regulations involved. The chapter starts with an overview of the technologies used to encapsulate the ingredients and to apply them to the textile. This is followed by examples of some cosmetic functionalities, e.g. moisturising or physiological cooling and substantiation of the efficacy. This is followed by a short description of examples of guidelines and legal aspects that shape regulatory framework surrounding cosmetotextiles. A short outlook will wrap up this chapter.

6.2 Application and release technologies

Developing and producing effective cosmetotextiles which actually provide valuable benefits for consumers for a certain number of days of wear is not an easy task. On the one hand, usually large amounts of cosmetic ingredients must be transferred to the skin while the cosmetotextile is being worn but, on the other hand, as little as possible should be lost when the textile is washed. Different approaches have been undertaken to resolve this tricky equation, whereby, historically, the main focus of interest has typically been on the retention during washing aspect with (too) little attention being given to the aspect of transfer. Some of the proposed solutions are:

- The co-extrusion of cosmetic ingredients into fibres. This has been done for aloe vera and vitamin E in polyamide yarn.[1]
- The concurrent application of emulsified cosmetic ingredients and polymeric binders onto fabrics, using the fibres themselves and the polymeric film as an entrapment system. This technology is sometimes called 'composite finishing'. One approach is described in patent application WO2006015718 (A1).[2]
- The binding of entrapped cosmetic ingredients onto the surface of the fibres/fabrics. Examples of entrapment technologies are complexation, absorption into microparticles and, most importantly, nano- or microencapsulation.

Table 6.1 presents a comparative assessment of these approaches.

In the following section we will focus on microencapsulation since it is by far the most commonly used approach. Indeed, the term 'cosmetotextiles' is often understood as a synonym for microcapsules on textiles.

6.2.1 Entrapment technologies

Quite a number of cosmetic ingredients are heat sensitive, prone to oxidation or are volatile. 'Micropackaging' or entrapment via microencapsulation or complexation enables sensitive cosmetic ingredients to be safeguarded from deleterious processes such as degradation by oxidation or polymerisation during drying and/or heat setting processes and garment storage. Volatile ingredients, e.g. perfumes and essential oils, are prevented from evaporating thus improving their permanence and longevity.

© Woodhead Publishing Limited, 2011

Table 6.1 Comparison of exemplary application and release technologies

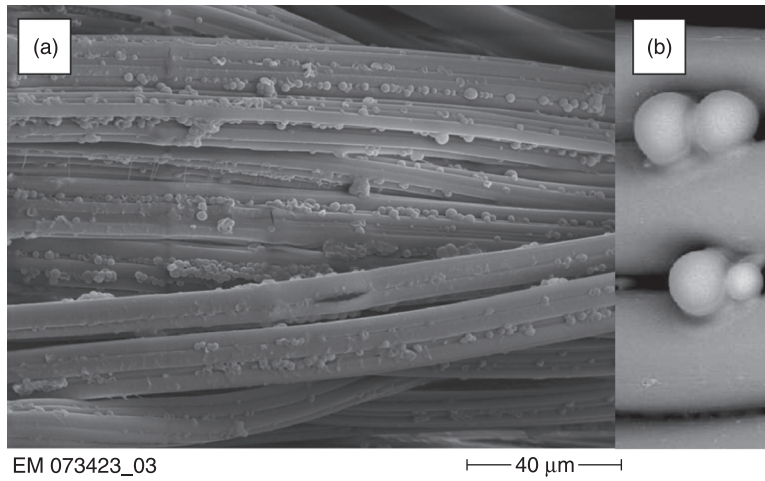
	Scope of application	Loading capacity	Wash resistance	Transfer to the skin
Co-extrusion	Very limited to extremely robust ingredients	Low to medium	Outstanding	Negligible
Composite finishing	Broad but not for water soluble or very sensitive or volatile ingredients	Very high	Good, depending on fibre and binder type	Fair to good
Complexing (cyclodextrins)	Very specific to a small number of ingredients	Medium to high	Fair	Limited
Micro-encapsulation	Very broad but largely limited to water insoluble ingredients	High	Good, depending on binder type	Fair to good

Microencapsulation

Microencapsulation is by far the technology most used to 'micropackage' cosmetic ingredients for application onto textiles. Microcapsules suitable for cosmetotextiles have mean diameters typically ranging from approximately 1–10 μm because the diameter of the single filaments textile yarns are composed of ranges from about 5 μm for microfibres to about 30 μm for coarse wool (Fig. 6.1). Microcapsules can be modified in size, mechanical robustness and permeability to customise the release profile to best fit the intended functionality. However, release by diffusion is generally not desired in cosmetotextiles because of the stability requirement during storage before wear. Because of their versatility and cost effectiveness, urea or melamin-formaldehyde based microencapsulation has been the most commonly used technology for cosmetotextiles. The initial step is to emulsify a liquid, hydrophobic blend of cosmetic ingredients with the help of an anionic polymer and mechanical homogenisation. The polymer is then cross-linked with a reactive urea or melamin-formaldehyde pre-polymer. Free formaldehyde reducing technologies round-off the process. Since most of the residual free formaldehyde is removed during the drying/curing steps which take place at the end of the textile finishing process, compliance with the limits of the Oeko-Tex Standard 100®, Class 2 (< 75 ppm) or even Class 1 (not detectable; i.e. usually understood as less than 20 ppm) can be achieved.[3] Class 2 covers textiles worn next to the skin while Class 1 covers textiles for babies.

A number of other encapsulation technologies have also been used, in particular the polycondensation (e.g. polyurea, polyurethane, polyester or polyamide) of a

© Woodhead Publishing Limited, 2011



6.1 Microcapsules: (a) microcapsules on polyamide knitwear; (b) microcapsules and visible binder.

solid shell around the cosmetic core and complex coacervation. Microcapsules produced with shell formation by polycondensation are well suited for cosmetotextiles but require specific developments for each type of content and careful attention must be given to residual monomer issues. Complex coacervation has the beauty of allowing the usage of natural polymers and has practically no risk of involving the microcapsule content in shell building chemical reactions. However, these microcapsules tend to have less mechanical robustness than the urea or melamin–formaldehyde based capsules.

Complexation with cyclodextrins

Another possible approach is based on cyclodextrins, which are bucket-shaped molecules composed of six to eight glucose units and are enzymatically derived from starch. They have the capability of building protective complexes with a variety of molecules, including cosmetically relevant ones like menthol, caffeine or α-tocopherol (vitamin E). These complexes can be attached onto fabrics with the help of a binder. Reactive polyurethanes have been reported to be particularly suitable for this purpose and initial evidence for transfer to a collagen-based skin model has been published.[4]

6.2.2 Binding technologies

Although covalent grafting of microcapsules especially onto natural fibres has been described,[5] the most common fixation involves the usage of an adhesive

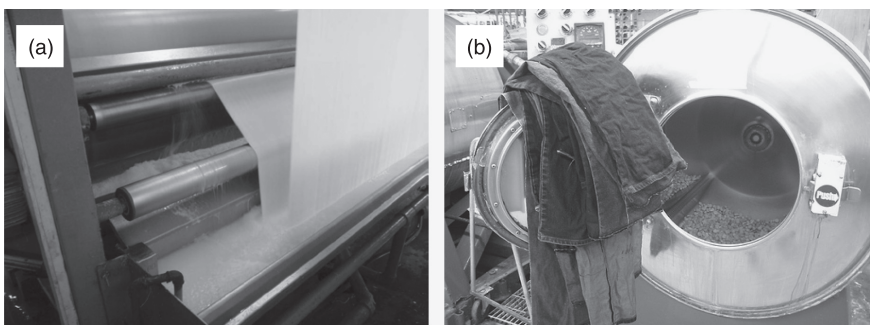
© Woodhead Publishing Limited, 2011

generally called binder specifically suited to the cosmetic and textile system used and which also exhibits good skin compatibility. Often used binder types are cross-linkable silicones, polyacrylates, EVAs (polyethylene-vinyl acetate) and polyurethanes. A certain amount of binder, typically 0.25% to 4.0% (dry matter per weight of fabric), is required to effectively bind the microcapsules, complexes or loaded particles to the fibres and to minimise their loss during washing. The release rate of the encapsulated cosmetic ingredients themselves can also be tailored by varying the amounts and types of binder used. Large amounts of binders which completely cover the microcapsules ('igloo' type) give better protection against breakage during wear and also retard the release of the cosmetic ingredients onto the skin. An additional role of the binder and of possible further additives is to impart to the garment other more classic but nevertheless important properties such as resistance to soiling, appealing handle or moisture management.

6.2.3 Finishing/application technologies

Two major methods of application which are very common in the textile finishing industry are generally used: (i) the padding process, and (ii) the exhaust process.

During the course of the padding process, the fabric is first run through the finishing bath (Fig. 6.2a). This bath contains an aqueous dispersion of microcapsules along with the binder as well as auxiliaries such as softeners or wetting agents. After emerging from the bath, the fabric is squeezed by a pair of rubber rolls with a constant pressure in order to reach a defined wet pick-up level. It then travels through a heat setting oven for drying and cross-linking of the binder. The fabric resides in the oven for a few seconds to 1–2 minutes at temperatures of 105°C to 140°C. Binders with low curing temperatures are obviously preferable. Pad application is called a forced process because the level of (cosmetic) finish on fabric is directly determined by the bath concentration and the pick-up level, assuming that no ingredients are volatilised in the oven.



6.2 Application of cosmetic finish via (a) padding and (b) exhaust.

© Woodhead Publishing Limited, 2011

The exhaust process uses a different principle. The fabric or garments are introduced into a closed vessel (generally a dyeing apparatus) with an initial quantity of water (Fig. 6.2b). The microcapsule dispersion, the binder, the auxiliaries and possibly acids/bases for pH adjustment are then metered into the vessel at defined times, speeds, temperatures and pH in such a way that the microcapsules and the binder ultimately end up as evenly and completely as possible on the textiles. The process is generally a combination of exhaustion and controlled precipitation, a sophisticated version of the way softeners work in the domestic washing machines.

Application of the microcapsules via padding allows a high degree of variability in the binder-to-microcapsule ratio. Exhaust application, which is the standard finishing process for hosiery and garments, e.g. jeans, is far more complicated, requires a very precise steering of temperature and pH, and greatly limits the choice of binders since few of them exhaust well.

Other finishing processes play a less important role in cosmetotextile production, but they are possible options too: spraying, printing and coating. Spray application is a good option for the application of microcapsules to selected parts of jeans. Printing and coating processes allow the preferential application of microcapsules to one side of the fabrics. This is beneficial for the transfer of the cosmetic ingredients to the skin provided the microcapsules are not embedded too deeply in the cross-linked polymers involved.

6.2.4 Quality control

Cosmetotextiles should be high quality textiles even before a cosmetic finish is applied to them. This entails that, above all, such textiles should be produced in mills with an outstanding quality management system and preferably an independently audited one. Traceability must be ensured, detailed standard operating procedures, including those for cleaning (avoidance of cross-contamination) and packaging, must be available and a commitment to comply with them in all cases and at all times must be evident throughout the organisation. Compliance with standards like Oeko-Tex® 100 and Oeko-Tex® 1000 is highly desirable.[3]

Cosmetic microcapsules (and any other cosmetic ingredient containing product) for cosmetotextiles should be produced in a facility complying with the principles of cosmetic Good Manufacturing Practices (cGMP; ISO 22716).[6] Assuming that a well defined application procedure for the cosmetic finish is in place, further steps are needed to determine that the cosmetic finish has (i) been applied evenly and at the right amount (initial loading), and (ii) has the required permanence or wash resistance.

Initial loading

Verifying the level of a cosmetic finish is not an easy task considering the complexity of the matrix it represents and the complexity of the cosmetic formulation itself. A formulation aiming at reducing the outer signs of cellulite,

© Woodhead Publishing Limited, 2011

for example, will tend to be composed of quite a number of single ingredients: emollients, vitamins as antioxidants, emulsifiers, specific anti-cellulite/slimming active ingredients and possibly fragrance oils. It is hence indispensable to select lead substances which can serve as tracers for the quantification of the total finish on the fabric. Ingredients such as vitamin E, acetate, caffeine, squalane, well defined triglycerides and key molecules in essential oils are good examples of possible tracers which can be quantified precisely and reliably. Active ingredients upon which precise performance claims are based must be quantified in any event to comply with legal requirements.

Quantification methods are suggested in CEN/TR 15917:2009.[7] The first step always involves the solvent extraction of a small sample of fabric. There is unfortunately no universal method which can be used for any ingredient in any microcapsule on any type of textile. A specific validation is necessary every time. It must be ensured that the extraction is quantative and the ingredients are not degraded. Extraction at moderate temperatures with solvents such as acetone, acetonitrile or blends thereof has proven to be suitable in many cases. If needed, ultrasound treatment can be included. Oxygen-free solvents are sometimes required for the extraction of essential oils to avoid their peroxidation. The quantification of the tracer substances in the extract is relatively straightforward with GC/MS or HPLC as the methods of choice.

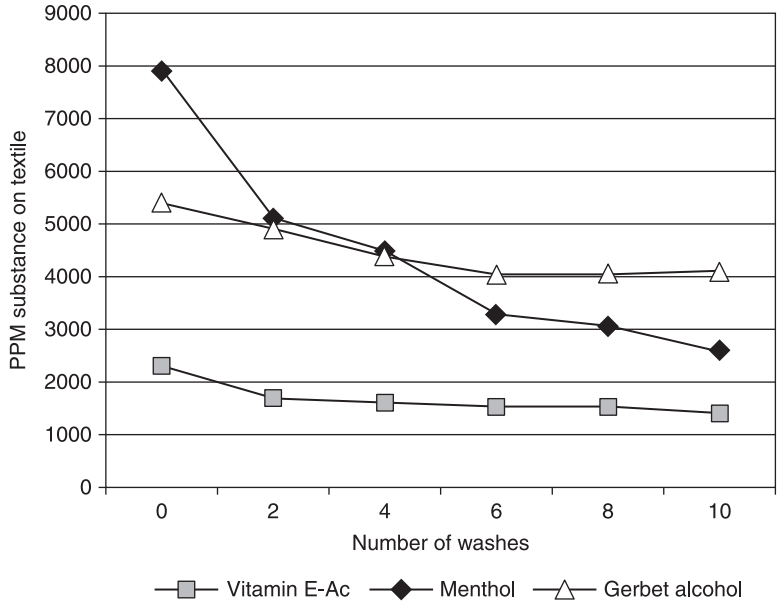
One of the most critical issues while quantifying the initial cosmetic loading of cosmetotextiles is sampling. Textile fabrics tend to be clearly far from perfectly uniform. Extraction is generally performed on just a few grams of fabric while many tons or many thousands of garments are being treated with the finish. This leads to some variability in the extraction results. Hence, well thought through sampling strategies are indispensable in order to obtain a reliable picture of the actual cosmetic loading and to be able to define relevant and realistic specifications.

Wash resistance

Wash resistance, which is more generally called ‘care resistance’ in CEN/TR 15917:2009, is the amount of cosmetic loading left on the textile after a number of washing cycles.[7] Appropriately sampled textiles are washed according to a standardised procedure with an ISO standardised detergent. The residual amount of cosmetic ingredients on the fabric is then determined in just the same way as for the initial loading. The washing procedure selected and the inclusion of tumble drying should reflect the care recommendation given to the consumers for the cosmetotextile. After ten wash cycles, residual levels of the cosmetic constituents generally lie between 20% and 60% (Fig. 6.3), although, due to their physical properties, volatile ingredients tend to be less permanent than non-volatile ones.

It is important to point out that determining the wash permanence is essentially a control of the quality of the finishing process. It verifies that the binder cross-linking which is responsible for the permanence of the finish has

© Woodhead Publishing Limited, 2011



6.3 Example of a wash permanency curve. The content of the specified tracer molecules in the textile following defined washing steps is depicted.

been properly done. There is little correlation between the wash resistance behaviour of a cosmetic finish and the effect it may generate on the skin of a wearer over days. On the one hand, if all of the initial cosmetic loading is largely washed out after just one or two wash cycles, there will hardly be any cosmetic effect after the textile has been worn for a very few days. On the other hand, a very strong wash resistance is generally a reliable hint to very little transfer to the skin taking place: the cosmetic ingredients built into the textile are only of use provided that sufficient amounts are transferred to the skin when wearing the textile. Generally, it is preferable to secure a significant transfer leading to a clear effect on the skin for a few days only rather than to maximise wash resistance which tends to imply that only small and probably ineffective amounts are transferred over a longer period of time. It is then better to rely on some reloading solution to refresh and maintain effects.

6.3 Functionalities of cosmetotextiles and performance testing

Cosmetotextiles are a unique combination of fabrics and incorporated skin care ingredients. As such, not only does the developer of a cosmetotextile need a high degree of expertise in the area of textile technology but also of the skin and how

© Woodhead Publishing Limited, 2011

cosmetics convey their effects. In addition, the claimed effects need to be demonstrated. In the following sections a short overview of some relevant aspects and possible approaches to claim substantiation will be given.

6.3.1 Skin

The skin is considered to be the largest organ of the body. With a surface area of approx. 1.8 m^2, the skin accounts for an estimated 15% of our body mass. The skin can be divided into three main compartments: the epidermis, the dermis and the hypodermis (contains the adipose tissues and muscles), whereby the latter is not always considered to be part of the skin.

The layer targeted by classic cosmetics is the epidermis. This layer is composed of cells which proliferate, wander upwards thereby changing their shape and function, a process termed differentiation, until they form the very outer layer of the skin, the stratum corneum. The water content is thereby greatly reduced from approximately 70% (basal layer) to 15% (stratum corneum). During the differentiation process, the cells are successively filled with large amounts of proteins, predominantly keratins, and the intercellular spaces are filled with lipids. The terminally differentiated cells of the stratum corneum are often termed corneocytes. They are compact protein-rich dead cells and are surrounded by the lamellar lipid layers typical of the stratum corneum. Because the corneocytes with their extracellular matrix give the impression of having a wall-like structure, the stratum corneum is often described with the help of the brick (corneocytes) and mortar (extracellular lipids) model. As the epidermis and stratum corneum are constantly being renewed, the corneocytes are continuously sloughed off (desquamation). The formation of the epidermis and stratum corneum is a dynamic process with a turnover time of approximately 30 days.[8,9] Due to the unique composition and structure of the stratum corneum, it forms the major barrier of the skin to environmental influences and prevents the human body from dehydrating.

6.3.2 Cosmetics: definition and functionalities

According to the European Cosmetics Directive (76/768/EEC) Article 1: 'A 'cosmetic product' shall mean any substance or preparation intended to be placed in contact with the various external parts of the human body (epidermis, hair system, nails, lips and external genital organs) or with the teeth and the mucous membranes of the oral cavity with a view exclusively or mainly to cleaning them, perfuming them, changing their appearance and/or correcting body odours and/or protecting them or keeping them in good condition'.[10] Most countries have their own regulations and definitions.[11–13]

Typical cosmetic functionalities are enhancing skin moisturisation, firmness or elasticity, UV protection, skin whitening or tanning, reduction of the outer appearance of cellulite, sebum regulation, anti-wrinkle, deodorant and/or

© Woodhead Publishing Limited, 2011

antiperspirant properties, perfumes and oral hygiene (toothpastes, mouthwashes, etc.). A short glossary of functions can be found at the European Commission's cosmetic ingredient website.[14]

6.3.3 Cosmetotextile-specific aspects

The cosmetic functionality defines the amount of a cosmetic product that are required to achieve efficacious performance. Skin care effects, such as moisturising and slimming, require large amounts of the cosmetic product to be transferred to the skin in order to achieve perceivable effects whereas fragrances only require the release of very small amounts to achieve effects. The efficacy of typical cosmetic moisturising creams is usually demonstrated in clinical tests by applying 0.5 to 2 mg of the cream per cm^2 skin onto the tested area. An efficient cream should then perform well at 0.5 mg/cm^2. If the concentration of the moisturising ingredients in the cream is 20% (80% being water), this would correspond to a daily dose of 0.1 mg/cm^2. To achieve this dosage, an average pantyhose covering an average of 1 m^2 of skin should contain 1000 mg of the cosmetic ingredients. A 20 den (22 dtex) pantyhose which weighs approx. 25 g must hence carry 1 g, i.e. four per cent of moisturising ingredients in order to deliver the efficacious dose for one day. Based on our experience, four per cent is close to the upper loading limit for cosmetics on textiles. This model calculation therefore suggests that moisturising efficacy can only be expected for one to possibly two days for the pantyhose. On heavier textiles, maintenance of cosmetic effects, e.g. moisturising, can be expected to last for five to ten days of wear if the textile is hand washed or mild laundering takes place. Fragrances may have a more lasting effect depending on the construction of the microcapsules, fabric, etc. It is also relatively difficult to prevent water soluble actives from being completely washed away during initial laundering. This places certain challenges on formulation, microencapsulation, etc. and typically only lipophilic ingredients can be used. Use of products to reload the textile, e.g. sprays containing the cosmetic formulations required, can prolong the efficacy of the cosmetotextile (Fig. 6.4).

Another aspect that needs to be taken into consideration is the design of the cosmetotextile. In order to maximise efficacy, the fabric composition and construction, garment design and cosmetic finish all need to work together to achieve the best effects. Cosmetotextiles with slimming effects will most likely work well if designed as a pair of elastic leggings with some degree of progressive non-medical compression or as tight jeans. This design allows close contact between the textile and the skin of the problem zones, thereby possibly generating a massage effect and which allows an adequate amount of the cosmetic product to be transferred from the fabric to the skin.

6.3.4 Claim substantiation

According to the European Cosmetics Association (Colipa) guidelines for the evaluation of the efficacy of cosmetic products (2001), a cosmetic claim is any

© Woodhead Publishing Limited, 2011

6.4 Examples of reloading applications: Spray reloads, packet reloads or foam reloads.

public information on the content, the nature, the effect, the properties, or the efficacy of the product.[15] The EU and many countries have their own regulations governing what and how effects can be claimed. Guidance documents available from various countries give support how acceptable claims can be formulated.[16,17] Care must be taken not to cross the line between medical, medical advice and cosmetic claims. Moreover, claims should not be deceptive or mislead the consumer. Within the Cosmetics Directive, article 7 requires proof of the effects claimed for cosmetic products, where justified by the nature of the effect or product and this proof should be made readily available to competent authorities. In this context, it should be mentioned that additional national and international legislation other than the Cosmetics Directive also needs to be observed, e.g. advertising laws, regulations governing textiles, etc.

A plethora of cosmetic claims exist and scientifically sound methods should be used to substantiate these claims. Typical cosmetic claims are variations on the theme of conveying moisturising effects, reducing wrinkles, making skin feel

© Woodhead Publishing Limited, 2011

smoother, increasing hair volume or gloss, etc. When deciding on how to substantiate a claim, it is important to take the following points into account: (i) what is being claimed, (ii) where and how does the product act, (iii) what parameters are changed, (iv) what methods are suitable to detect these changes, and (v) what is the target group. No legally binding standards are available for cosmetic testing although generally accepted methods are available. Comprehensive guidance describing the principles and procedures involved in claim substantiation have been published, e.g. by Colipa (2008) and Cosmetics, Toiletry and Perfumery Association (CTPA) (2008).[18,19] Claims generally fall into two categories: subjective and objective claims. Subjective claims, e.g. 'my skin looks better', cannot be measured using instrumental methods. These types of claims are typically substantiated using methods such as questionnaires. Data for objective claims, e.g. 'moisturises the skin', can originate from instrumental measurements (e.g. corneometry to measure skin surface moisture, cutometry to measure skin elasticity, sebumetry to measure skin surface lipids, etc.), but also via sensory assessments, questionnaires or via clinical assessments made by trained judges. In general, the gold standard for claim substantiation is a well conducted test with human volunteers. Data obtained using *in vitro* methods or other non-human tests can be used to generate additional information. Published data can lend further support to a claim. In this context, it should be noted that when tests are performed on humans, volunteer safety is of utmost importance. Therefore a toxicological assessment of the test product is necessary and the basic principles of good clinical practice should be observed, e.g. volunteers must give their informed consent prior to testing, may discontinue the study at any time they wish, test results should be well documented, etc.

6.3.5 Performance testing

The textile must release the cosmetic ingredients built into it and allow their transfer to the wearer's skin to be considered a cosmetotextile. Furthermore, the amounts transferred must be sufficient to ensure that cosmetic benefits are possible. In the following sections, studies predominantly conducted by our company with cosmetotextiles harbouring the cosmetic functionality 'moisturising' will be described as an exemplary approach for demonstrating the transfer of the cosmetic constituents from the cosmetotextile to the skin and substantiating claims and function via objective methods. Examples of claim substantiation via subjective consumer studies will be briefly discussed for the functionalities 'cooling' and 'outer appearance of cellulite/slimming'.

Skin transfer studies

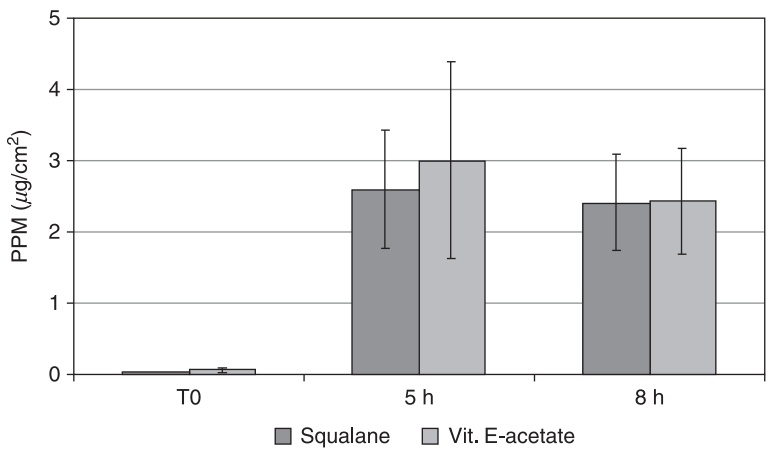
In contrast to typical skin care products where the product is applied directly to the skin, the principle behind cosmetotextiles is the gradual transfer of the skin care

© Woodhead Publishing Limited, 2011

formulation from the textile to the skin during wear. The amount of a skin care formula that can be loaded onto the textile is in part dependent on the material and the application procedure. The textile must also release the cosmetic in adequate amounts to obtain a cosmetic effect. As discussed above, if a sheer pantyhose (20 den) is loaded with four per cent of its weight with the cosmetic, most of the cosmetic will have to be transferred within one to two days to achieve efficacy.

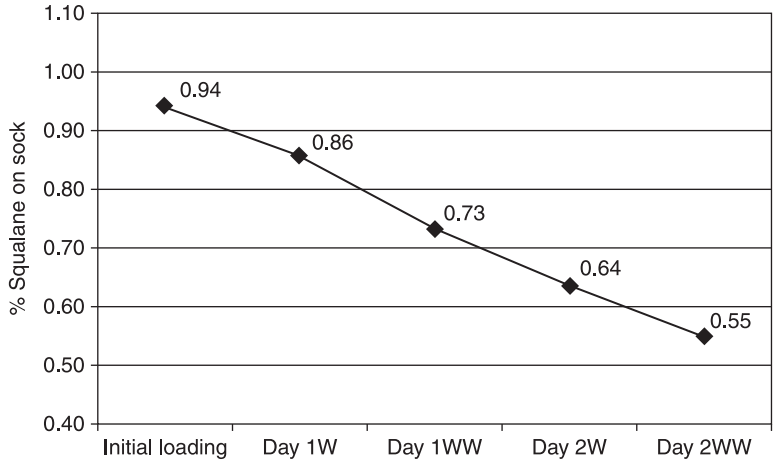
In initial studies, transfer from textiles to the skin was examined. Transfer was demonstrated using 20 human volunteers wearing a model cotton sleeve treated with microcapsules containing squalane and vitamin E acetate. After five and eight hours, the transferred substances were extracted from the skin surface of ten volunteers per time point using ethanol as a solvent. The results demonstrated that cosmetic ingredients are transferred from the textile to the skin (Fig. 6.5).

In order to allow a first estimate of how much of the cosmetic contained in the cosmetotextile is transferred to the skin during wear or lost during laundering, a wear and wash test was conducted using socks (cotton/polyamide/elastane: 80/17/3). A total of 30 volunteers with dry skin were asked to wear a sock treated with a moisturiser. Volunteers were asked to wear the socks for at least eight hours per day and the socks were washed with a defined mild detergent. During the course of the study, the samples of the socks of three volunteers were analysed for the tracer substances after one day of wear (day 1: wear). Samples from the same socks were analysed again after washing (day 1: wear and wash). The socks of the remaining volunteers were also washed and worn for a second day. The socks of the next three volunteers were then analysed before and after washing (day 2: wear and wash), etc.



6.5 Transfer of a cosmetic product from the cosmetotextile to the skin. The results depicted are the mean amounts extracted from the skin of 10 volunteers per time point. Significant amounts were transferred to the skin ($p < 0.05$) after 5 and 8 h of wear.

© Woodhead Publishing Limited, 2011



6.6 Wash and wear test. Socks were worn by volunteers and subsequently washed (Day 1W denotes day 1 of wear; Day 1WW refers to day 1 after wear and subsequent wash). At each time point, the amount of the tracer substance squalane found in the socks of three volunteers was measured.

The results revealed that, under these conditions, approximately equal amounts of the test formulation were being transferred from the socks or washed out (Fig. 6.6).

Efficacy testing via objective measurements

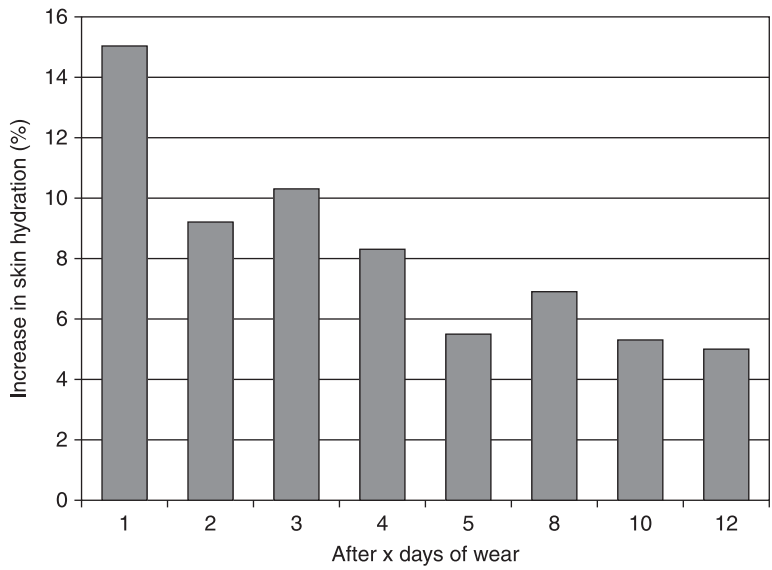
The presence of an adequate amount of water in the stratum corneum plays an essential role in skin surface appearance and properties. A sufficiently hydrated skin will appear smoother, softer and will be more flexible than rough dry skin. There are two major types of moisturisers; humectants and occlusives. Humectants help to keep skin moisturised by attracting and binding moisture; emollients produce a certain grade of occlusiveness thus slowing the evaporation of moisture from the skin. Skin surface moisture is typically assessed using corneometry. The underlying principle of corneometry is the measurement of the epidermal capacitance which varies depending on the hydration state of the stratum corneum. Skin hydration is dependent on various factors, e.g. sweating due to heat or exercise, time of day, body region, etc. It is therefore important to conduct these experiments under standardised conditions and after acclimatisation in climate controlled rooms.

To ascertain whether wearing a cosmetotextile can convey beneficial cosmetic effects to the skin, in this case improved skin hydration (moisturising), a study with 20 female volunteers with dry to very dry skin was conducted at an independent test institute. The volunteers were asked to wear an untreated sock on one side and a sock treated with a moisturising finish (Skintex® Monoi) on the

© Woodhead Publishing Limited, 2011

other side for eight hours a day for 12 days. Prior to initial use of the socks, measurements of skin surface via corneometry were taken at defined sites on the shins and ankles with ten measurements per test area used to define the mean hydration of the area. Further measurements were made on days 1, 2, 3, 4, 5, 8 and 12 after an acclimatisation time of 30 minutes without socks at 21°C and a relative humidity of ±5%. The subjects were instructed to hand-wash the socks daily. With the exception of days 5 and 10, a statistically significant increase in skin hydration was observed on the treated side. The results are depicted in (Fig. 6.7). The greatest increase was observed after one day of wear and gradually decreased over the study period, which would coincide with a gradual depletion of the cosmetic from the sock over the observation period.

Cosmetotextiles can also add beneficial properties to medical textiles. Regular use of medical compression stockings can lead to skin dryness and itching can result. An interesting study was presented by Jünger *et al.*,[20] in which the skin of 20 volunteers following wear of compression stockings treated with a moisturising finish ((Skintex® Monoi Med) were compared to skin of 22 volunteers wearing untreated stockings. Volunteers were asked to wear the stockings for eight hours



6.7 Wash and wear efficacy test to assess skin hydration. Volunteers (n = 20) wore a treated and untreated sock in a left/right comparison over 12 days. The results depict the differences in per cent between the treated and untreated sides after correction of the baseline values. The sock with the moisturising finished significantly ($p < 0.05$; Wilcoxon rank test) increased skin surface hydration compared to the untreated side on all days with the exceptions of day 5 and day 10. Error bars were omitted to increase clarity.

© Woodhead Publishing Limited, 2011

per day for one week. Skin hydration, roughness and barrier function were assessed on day 1 and day 7 of the study. Assessment of skin hydration was conducted using corneometry (Corneometer®), roughness was assessed via the fast optical *in vivo* topometry of human skin technique (FOITS, Dermatop®) and skin barrier function was evaluated by determining changes in transepidermal water loss (Tewameter®). Itching was assessed via volunteer assessment. The results of the study revealed that side effects of wear of compression stockings, namely itching, impaired barrier function evidenced by increased epidermal water loss, skin dryness and roughness, can be reduced by treating the fabric with a moisturising finish. Although not addressed by this study, it does allow the hypothesis that cosmetotextiles can modulate skin thereby enhancing the patient's sense of wellbeing which in turn could result in increased compliance and perceived quality of life.

Efficacy testing via subjective measurements

Claims can also be substantiated via the use of consumer tests. These types of tests give information on consumer acceptance and perceived performance. In particular home use tests can yield valuable information as they are carried out in the consumer's actual home environment. Perceptions, preferences and acceptance cannot readily be assessed by objective measurement. Parameters relevant to these types of information are therefore generally assessed via questionnaires and/or interviews.

Studies were carried out to ascertain the subjective feeling of 'cooling' when wearing a Skintex® Supercool treated T-shirt during exercise. Among the encapsulated ingredients conveying cooling effects were menthol and derivatives thereof. These types of substances do not bring about physical cooling, in which a cooling sensation is imparted by the decrease of the outside temperature, but exert their effects via physiological action. This takes place via the stimulation of specific receptors in the skin. Hence, objective measurements are not feasible. The study revealed that 63% of the wearers still perceived a cooling effect after the T-shirts were washed six times. The majority of the volunteers also perceived the initial cooling effect at the onset of sweating. By applying this type of study, valuable information can be obtained which is not possible via objective measurements.[21]

Jeans treated with a 'slimming/anti-cellulite' finish (Skintex® Slimming) were tested in a home use test. Exemplary parameters to be evaluated were the changes in consumer assessed skin hydration, skin feel and changes observed in the outer appearance of cellulite generated by wearing the jeans. The aim was to obtain information on the perceived benefits, preference for reloading applications and acceptance of the cosmetotextile. Each participant visited the test centre, was given two treated jeans (97% cotton; 3% elastane) in a size they found acceptable and was instructed on how to use the reload. They were asked to wear the jeans

© Woodhead Publishing Limited, 2011

for six weeks for at least five days per week and eight hours per day. Participants were asked to wash the jeans in a washing machine using a detergent for delicates and to air dry the jeans. Half of the group received a packet reload; the other half received a spray reload to be used after washing the jeans (see also Fig. 6.4). A total of 160 participants were recruited and questionnaires were completed after four and six weeks of wear.

The information obtained via the questionnaires revealed that, e.g. after four weeks of wear, 78% of the participants found the jeans pleasant to wear; after six weeks 74% found them pleasant to wear; application of the cosmetic via cosmetotextiles was perceived as being easier than a conventional cosmetic cream application by 93% of the participants, a slight to strong improvement of the state of the thighs and their appearance was perceived by 69% after four weeks and 74% after six weeks of wear and the spray reload application was favoured over the packet reload application.

6.4 Safety evaluation and other regulatory aspects

This section will focus on European legislation on cosmetics as this is an area with which many textile manufacturers may not be familiar. The Cosmetics Directive 76/768/EEC sets the legal framework for cosmetics within the European Union.[10] The Cosmetics Directive was first adopted by the member states in 1976. Since then, it has undergone seven amendments that reflect new trends and challenges concerning cosmetic products; the last of which reflects the concerns for animal welfare and includes the regulations for the phasing out of animal studies to be used for cosmetic purposes. This Directive has now been transformed into a Regulation and places more emphasis on consumer safety aspects, claim support, animal welfare and cosmetovigilance. This regulation (EC No 1223/2009) on cosmetic products was adopted in 2009 and will fully come into force in 2013.[22]

In the case of cosmetotextiles, the question can be posed whether or not they can be classified as being cosmetics. The so-called borderline manual gives guidance on whether the Cosmetics Directive applies to certain products, e.g. cosmetotextiles.[23] According to this manual,

> the textile is neither a substance nor a preparation…. However, the textile may be the 'vehicle' to deliver a substance or preparation to the human skin. This substance or preparation, if it is intended to be placed in contact with the various external parts of the human body, with a view … to protect them or keeping them in good condition, falls within the scope of application of the Cosmetics Directive.

In other words, the cosmetic part of the cosmetotextile needs to comply with the Cosmetics Directive. It also states that other legislation, regulations or directives may also apply in parallel, i.e. any legislation relevant for conventional textiles must also be taken into account.

© Woodhead Publishing Limited, 2011

Cosmetotextiles contain cosmetic ingredients which need to be as safe as cosmetics applied via conventional means, e.g. body lotions. Qualified professionals are needed to ensure that toxicological data for the cosmetic ingredients and the textile auxiliaries used in the cosmetotextile's finish is available and the toxicological profile is satisfactory. Various questions concerning the safety of consumer products (non-food products intended for the consumer) in particular the safety of cosmetic products and ingredients with respect to their impact on consumer health, etc., are discussed by the Scientific Committee on Consumer Safety (SCCS; earlier known as SCCNFP or SCCP). Its output is usually in the form of opinions, statements, guidance documents, etc. In this context, a guidance document for assessing cosmetic safety has also been published by the SCCP, and is updated every few years.[24]

In order to better define various aspects applicable to cosmetotextiles and to initiate steps towards defining standards for cosmetotextiles, e.g. how to determine wash permanence, the CEN/TC 248 working group Nr. 25 drafted a technical report (CEN/TR 15917) which was submitted for formal vote and accepted in 2009.[7] It comprises sections with guidance on aspects such as labelling, determining wash permanence, conducting studies for claim substantiation and safety evaluation.

A multitude of other regulations apply to textiles themselves, e.g. The Directive on Textile Names (96/74/EC) requires the labelling of the fibre composition of textile products, some of which can be found in the CEN technical report.

6.5 Future trends

Textiles with claimed cosmetic effects were first introduced in Japan in the early 1990s. France followed in the late 1990s with Dim's moisturising and slimming pantyhose and Kunert in Germany with its 'first cream to wear' pantyhose. In the meantime, many small but also major textiles brands and retailers have launched cosmetotextiles, but these usually remain on the market for a few seasons only. The reasons for the lack of significant and sustainable commercial success are two-fold: First, most of these cosmetotextiles promised more than they were able to deliver. Very few of them came with performance claims based on state-of-the-art performance testing. Second, as this is a new technology, many consumers are skeptical of the concept of cosmetics embedded in textiles.

To date, most genuine cosmetotextiles have been launched with marketing communication insufficiently meeting the challenges of the existing credibility gap in the minds of consumers. Not surprisingly, the best commercial successes have been achieved via sales channels like tele-shopping or via catalogues which allow detailed information on the concept and the products. Cosmetotextiles will grow out of their market niche thanks to brands combining excellent product quality, compliance with rules such as those laid out in the CEN Technical Report 'Cosmetotextiles' and well thought through marketing campaigns. The progressive

© Woodhead Publishing Limited, 2011

involvement of traditional cosmetic brands will further strengthen the credibility of the cosmetotextile concept. It is likely that the most sustainable businesses will be created with cosmetotextiles and reload systems fully leveraging the convenience asset of 'automatic skin care' on large body surfaces. The moisturising functionality on medical compression textiles and the anti-cellulite/slimming functionality on hosiery, lingerie and garments designed for a good synergy between textile construction and cosmetic finish are likely to grow the strongest because they address clear and lasting needs of many consumers. With technologies further maturing, cosmetotextiles providing for example real hair growth retarding or self tanning effects may appear and bridges towards the area of medical patches may be established.

6.6 References

1 Information for these types of fibres can be found at company websites, e.g. www.novarelaloevera.com.
2 Mathis R, Sladek H, Fuelleborn M, Emini S (2008). *Finished Fibers and Textile Construction*. Patent application WO2006015718 (A1).
3 Oeko-Tex® Standards. Available: www.oeko-tex.com.
4 Zyschka R, Brückmann R, Kammerer B, Schreiber H (2004). Wellness-Finish with Vitamin E. *Textilveredelung*, 7/8: 10–13.
5 Y. Frere, L. Danicher, S. Berger. Capsules with a modified surface for grafting onto fibres. US patent No. 2009325438 (A1); French patent application: 02 05988 filed on May 5, 2002 entitled 'Fibres textiles greffées par des capsules composites' in the name of the CNRS and naming as inventors Y. Frere, L. Danicher and S. Berger.
6 ISO. *Cosmetics – Guideline on Good Manufacturing Practices* (GMP; ISO 22716). Available: www.iso.org or www.ikw.org.
7 CEN: CEN/TR 15917:2009. Cosmetotextiles. Available: www.cen.eu.
8 Downing DT, Stewart ME (2000). Epidermal composition. In *Dry Skin and Moisturizers: Chemistry and Function*. Loden and Maibach (eds.). CRC Press, London, pp. 13–26.
9 Haake A, Scott GA, Holbrook KA (2001). Structure and function of the skin: Overview of the epidermis and dermis. In *The Biology of the Skin*. Freinkel RK, Woodley DT (eds.). New York: The Parthenon Publishing Group, pp. 19–46.
10 European Union (1976). Council Directive 76/768/EEC of 27 July 1976 on the approximation of the laws of the Member States relating to cosmetic products (EU Cosmetics Directive) Available: eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1976L0768:20080424:en:PDF).
11 Australia: NICNAS Cosmetic guidelines, 2007. Available: www.nicnas.gov.au/Current_Issues/Cosmetics.asp.
12 CANADA cosmetic regulations. Available: http://www.hc-sc.gc.ca/cps-spc/person/cosmet/index-eng.php.
13 FDA Cosmetics. Available: www.fda.gov/Cosmetics/GuidanceComplianceRegulatoryInformation/default.htm.
14 EU CosIng List of functions. Available: (http://ec.europa.eu/enterprise/cosmetics/cosing/index.cfm?fuseaction=ref_data.functions).
15 Colipa. Guidelines for the evaluation of the efficacy of cosmetic products, 2nd edition (2001). Available: www.colipa.eu.

© Woodhead Publishing Limited, 2011

16 ASEAN Cosmetic claim guideline, Appendix III, 2007. Available: www.bfad.gov.ph/oldsite/ACCSQ%20COSMETIC/converted%20files/Appendix%20III_ASEAN%20Cosmetic%20Claim%20Guideline.pdf.
17 CANADA (2006). Guidelines for Cosmetic advertising and labeling claims (ISBN 0-662-49001-0). Available: www.hc-sc.gc.ca/cps-spc/alt_formats/hecs-sesc/pdf/pubs/indust/cosmet/guidelines-ld-eng.pdf.
18 Colipa. Guidelines for the evaluation of the efficacy of cosmetic products, 2008. Available: www.colipa.eu.
19 CTPA guide to Cosmetic Claims (2008). Available: www.ctpa.org.uk.
20 Jünger M, Riebe H, Haase H, Ladwig A (2006). Compression stocking for transdermal skin care (RCZ) 48 Jahrestagung der Deutschen Gesellschaft für Phlebologie. Available: www.medizin.uni-greifswald.de/haut/fileadmin/user_upload/lehre/2009_Wundkurs/Venotrain_micro_balance.pdf.
21 Mathis, R, Mehling A (2007). A cool approach to well-being with textiles. *Specialty Chemicals Magazine*, 27–28 November.
22 European Union (2009). The Regulation (EC) No 1223/2009 of the European Parliament and of the Council of 30 November 2009 on Cosmetic Products. Available: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:342:0059:0209:EN:PDF).
23 European Union (2007). Manual on the scope of application of the Cosmetics Directive 76/768/EEC (Art. 1(1) Cosmetics Directive) Version 4.0 (June 2007) (Borderline Manual) Available: (http://ec.europa.eu/enterprise/cosmetics/doc/manual_borderlines_version40.pdf).
24 SCCP. Notes of guidance. Available: (http://ec.europa.eu/health/ph_risk/committees/04_sccp/docs/sccp_o_03j.pdf).

© Woodhead Publishing Limited, 2011

7

Drug-releasing textiles

U. S. TOTI, S. G. KUMBAR, C. T. LAURENCIN, R. MATHEW and D. BALASUBRAMANIAM,
University of Connecticut Health Center, USA

Abstract: Conventional drug delivery formulations and systemic drug administration routes often fail to achieve therapeutic drug concentrations due to poor drug solubility and rapid body clearance. Controlled drug delivery strategies offer practical and effective alternatives to overcome several drawbacks of traditional dosage forms including prolonged drug release at required therapeutic concentration, site specificity and patient compliance. Though polymeric micro-/nanoparticulate and transdermal drug delivery systems have shown great promise they often require multi-step formulation procedures leading to production difficulties as well as varied properties that depend on polymer nature. Textile based drug loaded bioactive bandages have been very popular and cost effective for wound care applications. In recent years medicated textiles have emerged as promising alternatives that have the potential of being used as both topical and systemic drug delivery system. This chapter will provide an overview of drug releasing textile fabrication, characterization and their potential applications to treat various ailments.

Key words: antibacterial barriers, bioactive textiles, drug delivery, nonwoven drug eluting fabrics, bioactive scaffolds, wound dressings.

7.1 Introduction

Conventional oral and intravenous routes of drug administration are most popular, which require repeated drug administration to maintain therapeutic drug concentration. On many occasions, systemic drug administration suffers from poor drug bioavailability due to its incomplete absorption and/or degradation (Goldburg and Gomez-Orellana, 2003). In situations where the rate of drug elimination is very high the systemic drug concentration in the body rapidly rises and falls leading to either high drug concentration above toxic limits resulting adverse side effects or too low drug concentration, which is not enough to provide required therapeutic benefit. Further, conventional dosage forms lack target site specificity which is the main concern while administering anticancer and protein based specialty drugs (Torchilin and Lukyanov, 2003).

The aforementioned drawbacks associated with traditional drug administration can be effectively addressed by controlled/sustained drug delivery strategies (Ranade and Hollinger, 2004; Park, 1998). Contemporary controlled release strategies include formulations comprised of emulsions (Davis, 2004;

© Woodhead Publishing Limited, 2011

Constantinides, 1995), enteric coating (Watts and Illum, 1997; Maestrelli *et al*., 2008), and matrix based diffusion, erosion and dissolution systems (Pappas, 1997) as well as prodrugs (Järvinen and Savolainen, 2008; Stella and Nti-Addae, 2007; Greco and Vincent, 2008) and micellar systems (Francis *et al*., 2004; Duncan, 2003). Enteric coating method is generally used to protect the drug from the highly acidic pH environment in the stomach. In this method, solid drug dosage form will be coated with pH sensitive material which will dissolve specifically at intestinal pH releasing the drug. In case of matrix based systems, drugs will be entrapped in an insoluble or soluble matrix and will be released in a controlled and prolonged fashion. The drug release characteristics from these matrices greatly depend on a variety of parameters such as the properties of the encapsulating material, mode of encapsulation, concentration of the drug encapsulated, and the matrix architecture, which gives flexibility to control the rate of drug release to achieve therapeutic efficacy. For example, in the case of a cross-linked hydrophilic matrix, drug will be released by diffusion where the release rate can be controlled by altering the polymer cross-linking density. Surface erosion prevails in hydrophobic matrices and releases encapsulated drug as the matrix erodes layer by layer. Hydrogel based micro-/nanoparticulate matrix systems are used for the release of both hydrophilic and hydrophobic drugs (Kabanov and Vinogradov, 2009). Slow releasing tablets, stimuli sensitive hydrogels and micro/nanoparticulate systems are common examples of matrix based systems, for oral, local and systemic/intravenous drug administration respectively. However, production of consistent nanoparticles is complicated and hence may not be as economical as other matrix based systems.

Prodrugs are a class of drug delivery systems in which the drug is covalently conjugated to hydrophilic small molecules or polymers. Such systems are designed to improve drug solubility of sparingly water soluble drugs that are used for both enteral and parenteral administration. However, these systems fail to protect drugs from the degradation due to physiological environment. Micellar systems comprised of amphiphilic polymers with ability to self assemble into nanoparticulate systems that can physically encapsulate hydrophobic drug in the lipophilic core. Polymeric micelles release encapsulated drug by diffusion and erosion. Attempts are also made to fabricate micelles by covalently conjugating drugs to self assembling amphiphilic polymers (Jun *et al*., 2008). Generally, micellar delivery systems lack high drug load carrying capacity. Liposomes though carry high payloads of both water soluble and insoluble drugs, but lack stability. Several efforts were made to modify surfaces of above delivery systems with various functional groups and guiding molecules to achieve site specificity (Saad *et al*., 2008; Ding *et al*., 2006; Low and Antony, 2004).

Drawbacks of systemic circulations can be effectively addressed by delivering drugs through skin (transdermal drug delivery). These systems are found to be very efficient and attractive for the delivery of a variety of medications for pain, motion sickness, cardiovascular disease, skin cancer, female sexual dysfunction,

© Woodhead Publishing Limited, 2011

fungal/bacterial infections and variety of hormonal dysfunctions (Prausnitz *et al.*, 2004). Drug loaded membrane material applied on the skin can safely deliver drug to the specific site through skin permeation avoiding systemic route. However, the outermost layer, stratum corneum of the skin acts as a barrier and hence limits the selection and amount of drug to be delivered. Efforts have been continued to improve drug permeability and extend its applications to variety of sickness and wide range of drug candidates (Benson, 2005).

Hence, the ideal drug delivery system should be biocompatible, inert, mechanically strong, and comfortable for the patient, capable of delivering high payload, safe from accidental release, simple to administer, minimally off targeting and economical to fabricate and easy to sterilize. However, there is no single drug delivery system or approach that can be readily accepted for all the needs. In search of such an ideal drug delivery system, textiles offer promising alternatives having potential to overcome most of the negative aspects, if not all. The present chapter will discuss about the textile based drug delivery system fabrication, characterization and their potential applications to treat various ailments.

7.2 Classification of drug-releasing textiles

Textile based drug delivery systems are broadly divided into two categories such as woven and nonwoven drug eluting fabrics. These fabrics can be degradable or non-degradable based on the type and nature of fibers they are made from. In all these forms, individual fibers may contain bioactive agents or drugs within the fiber structure or drugs may be covalently attached to the fabric surface. Nonwoven fabrics produced by electrospinning process have gained much attention recently for variety of biomedical applications including drug delivery. Drug loaded long fibers in the form of monofilaments or their braids have also been developed and used as sutures for wound closures.

7.2.1 Drug-releasing woven fabrics

These systems require production of fabrics using fibers that are encapsulated with drugs or bioactive agents. Alternatively, woven fabrics can be treated with bioactive agents or drugs in presence of suitable physical or chemical modifiers to covalently attach bioactive moieties. In general woven fabrics will have drugs that are physically absorbed or adsorbed, coated, encapsulated or covalently conjugated on the fabric. Medicated woven fabrics offer precise geometry, pore structure and strength that is suitable for variety of biomedical applications apart from drug eluting properties. Drug loaded woven textiles are popularly used as bioactive bandages, artificial skin graft substitutes, scaffolds for tissue repair and regeneration, aromatherapy and other topical applications. (Perelshtein *et. al.*, 2008; Wollina *et al.*, 2003)

© Woodhead Publishing Limited, 2011

7.2.2 Drug-releasing nonwoven fabrics

Drug encapsulated nonwoven fabrics are manufactured by putting small fibers together in the form of a sheet or web like structures following entangling drug loaded fiber or filaments mechanically, thermally or chemically. Nonwoven fabrics can be produced to meet the specific requirements and used extensively as bacterial barriers, sterile wraps, wound dressings, caps, gowns, masks and draping (Whyte *et al*., 2005; Ohshima *et al*. 1987; Williamson *et al*., 2004; Blom *et al*., 2000).

7.2.3 Drug-releasing electrospun nonwoven fabrics: nanofibers

Drug releasing nonwoven nanofiber fabrics can be produced by polymer solutions and their melts via electrospinning process. A polymer–drug solution is made to pass through a small orifice where a high electric potential typically 5–30 kV is applied to initiate the polymer jet ejection from the orifice tip. As the jet travels, it makes a series of vigorous bending and stretching motions before it hits the grounded target resulting in nonwoven drug loaded fabric. It is possible to adjust the fiber diameter and align fibers in a particular orientation by manipulating electrospinning parameters such as applied electrical potential, polymer solution flow rate, working distance between spinneret and collector and target configuration to achieve desired mechanical properties and drug release patterns (Kumbar *et al.,* 2006, 2007a).

7.3 Fabrication and characterization

A variety of drug loading approaches have been adopted to prepare drug releasing textiles including coating, encapsulation, hollow fiber filling, ion exchange, inclusion complex and direct conjugation methods. The following sections will discuss these methods in detail.

7.3.1 Coating

The coating method is one of the simplest approaches in which drug is directly loaded on the fabric surface by dipping in drug solution or by coating with drug encapsulated micro- and nanoparticles (Ma *et al*., 2009). However, drug loading efficiency will greatly depend on the nature of the fiber material as well as the bioactive agent/drug. For example, drugs with higher affinity towards a polymer will readily form thin drug layer on the polymer surface. In many cases drug coated fabrics release significant amount of drug immediately following *in vivo* implantation. This inherent drawback makes it less popular and may not be suitable for releasing drugs for extended period of time. To circumvent this issue

© Woodhead Publishing Limited, 2011

Ma and co-workers coated cotton fabrics with a paste formulation comprised of drug microcapsules and adhesives (Ma *et al*., 2009). Such an approach could significantly reduce initial burst release of drugs and drug release was solely dependent on nature of drug micro/nanocapsule. In such formulations a greater challenge is to keep the drug loaded capsules attached to the fabric surface. Dubas and co-workers dip coated drug solutions on fibers in layers where nylon fibers were initially coated with a drug solution on which a layer of silk fibers were deposited (Dubas *et al*., 2006). This process was repeated in sequence to achieve controlled release of drug for prolonged period of time. Efforts were also made to coat silver nanoparticles in an attempt to create antibacterial surfaces via ultrasound (Perelshtein *et al*., 2008) and ion-beam (Klueh *et al*., 2000) irradiation. Free radicals created on the fiber surface upon exposure to radiation energy are known to be involved in forming covalent stable bonds with silver nanoparticles, creating antibacterial surfaces.

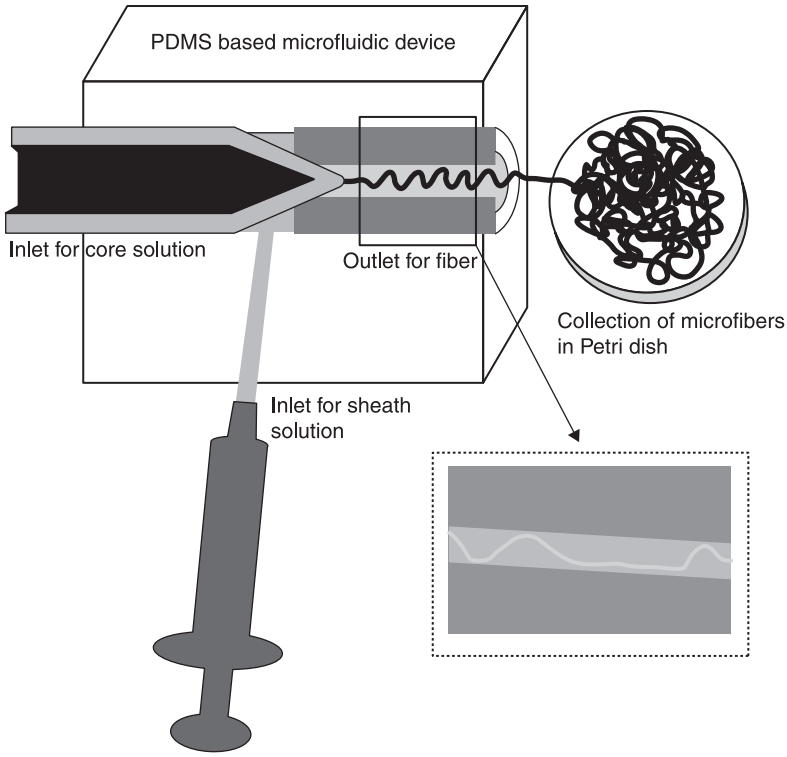
7.3.2 Encapsulation

Higher drug loading can be achieved within the fiber structures by soaking fabrics in drug solutions. The drug enters the fiber structure upon swelling via a diffusion process (Hou *et al*., 2006). This kind of encapsulation process is only applicable to fabrics that swell in drug solutions. Drug loading and its subsequent release is solely diffusion controlled and dependent on drug solubility and fiber swelling index.

Drug encapsulation in the textile during the fiber preparation is one of the most efficient methods (Nelson, 2002). Such an approach utilizes a homogeneous polymer–drug solution to fabricate fibers with suitable means. Hence both the drug and polymer have to be dissolved in a common solvent. This approach allows the required amount of drug loading and uniform drug distribution throughout the fiber structure without any extra effort. In the case of poorly soluble drugs in the chosen solvent system for dissolving a polymer, drug–polymer suspensions can be created by dispersing fine drug particles followed by agitation or exposing the system to ultrasonic waves. Thus the prepared homogeneous drug–polymer solution or suspension were subjected to extrusion using a microfluidic device (Hwang *et al*., 2008; Marimuthu and Kim, 2010), drawing, wet-spinning (Yu *et al*., 2009) and electrospinning (Kumbar *et al*., 2006; Xie and Wang, 2006) to produce drug loaded fibers. Several polymeric drug loaded systems were created using non-degradable polymers such as polyethylene, polyurethanes and polyethylene vinyl acetate copolymers, and also biodegradable polymers including poly(lactic acid), poly(glycolic acid), poly(orthoesters) and poly(phosphazenes).

In a microfluidic extrusion process a homogeneous polymer–drug solution in an organic solvent was injected through the core inlet as depicted in Fig. 7.1 and an anti-solvent for the drug–polymer solution by outer inlet making use of infusion pumps at identical flow rates simultaneously. Drug loaded fibers from the core

© Woodhead Publishing Limited, 2011



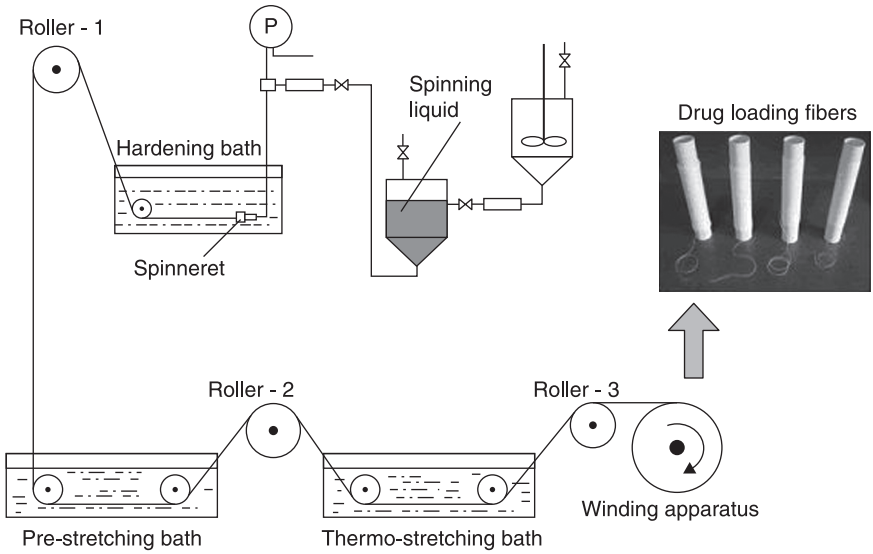
7.1 Schematic illustration of the microfluidic device for extrusion of microfibers where the inlet for the core contains drug–polymer solution in an organic solvent and sheath will have an anti-solvent for the solution. Upon contact with anti-solvent the polymer solution precipitates, producing drug loaded fibers. Optical micrograph of fiber from capillary outlet is presented as an insert. (Reproduced with permission from © Nature Publishers 2010, figure is adapted from Marimuthu and Kim, 2010.)

will be hardened upon contact with anti-solvent and extruded porous fibers were collected. This process is an improvised sol–gel method and outlined in Fig. 7.1.

In the wet spinning method of encapsulation, the bioactive agent containing the spinning solution is pressured out from the spinneret to become very fine streams. The streams are hardened and turned into fibers in the hardening bath followed by pre-stretching and thermo-stretching to produce bioactive molecule loaded fibers. The process is described in Fig. 7.2.

The aforementioned drug encapsulation methods, namely wet-spinning and the microfluidic extrusion technique, utilize an anti-solvent to harden drug loaded fibers. In such cases the efficiency of drug encapsulation may decrease depending on the nature of the anti-solvent, bioactive molecule and contact time that leads to partial dissolution of drug into anti-solvent.

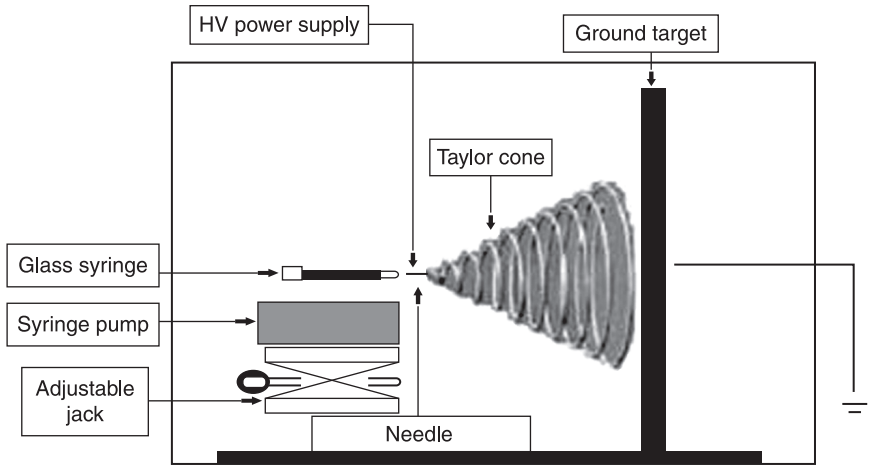
© Woodhead Publishing Limited, 2011



7.2 Process of drug loaded fiber production using wet spinning method. Spinning liquid containing polymer–drug suspension from the spinneret passes through hardening, pre-stretching and thermo-stretching baths to produce drug loaded continuous fibers. (Reproduced with permission from © Elsevier 2009, figure is adapted from Yu *et al.*, 2009.)

Electrospinning is one of the simple and elegant methods to produce drug loaded nonwoven fabrics comprised of nano- or microfibers for a variety of biomedical applications, including tissue engineering (Kumbar *et al*., 2006, 2007b). Electrospinning is driven by an applied electrostatic force to the homogenous drug–polymer solution or suspension. A typical electrospinning process is shown in Fig. 7.3, wherein an electric potential is applied to a pendent droplet of polymer solution or melt from a syringe or capillary tube. When the applied electrical potential exceeds the opposing liquid forces such as surface tension and viscosity a thin polymer jet ejects from the orifice. In low viscosity solutions, the emerging jet may break up into droplets called electrospraying (Kumbar *et al*., 2007b). In higher viscosity solutions the polymer jet undergoes a series of bending, winding, spiraling and looping motions resulting in ultra-thin fibers before it reaches the target. The electrospinning process is governed by various system parameters and processing variables which can be controlled to develop fibers from a wide range of materials with varying sizes and shapes (Jayaraman *et al*., 2004; Frenot and Chronakis, 2003; Theron *et al*., 2004). System parameters that can be varied to control resulting nanofiber morphology and diameters include polymer properties. Being a mild, efficient and highly flexible process, electrospinning can be used to directly incorporate both hydrophobic and

© Woodhead Publishing Limited, 2011



7.3 Schematics of the electrospinning process where positive terminal of the high power source is applied to the blunt end needle tip from which the homogenous drug–polymer solution exits. At an appropriate applied voltage the polymer jet ejects from the needle tip and thins down before it hits the grounded target. (Reproduced with permission from © American Scientific Publishers 2006, figure is adapted from Kumbar *et al.,* 2006.)

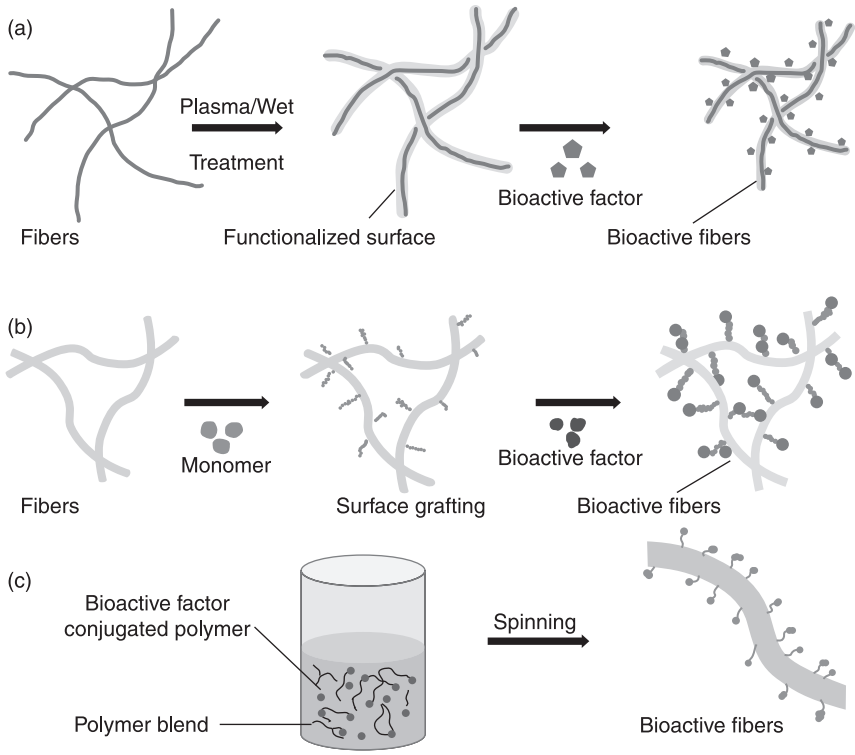
hydrophilic drugs/proteins within the bulk phase of fibers (Chew *et al*., 2005; Kumbar *et al*., 2006; Xie and Wang, 2006; Verreck *et al*., 2003a; Pornsopone *et al*., 2007).

7.3.3 Bioconjugation

In this approach a bioactive molecule or drug will be coupled to the textile surface by chemical (covalent bonds) or physical means to achieve controlled drug release as well as site specific drug delivery (Yoo *et al*., 2009; Kim *et al*., 2007). For conjugation it is required for the fabric surfaces to have readily available functional groups. Alternatively, functional groups can be created on the fabric surfaces using a variety of techniques, including plasma treatment, wet chemical method, grafting and co-spinning. A schematic presentation of these approaches is presented in Fig. 7.4. Procedural details of each of the processes can found elsewhere (Yoo *et al*., 2009).

Fabric surface treatment with plasma creates variety of functional groups depending on the gas used to create plasma (Zhu *et al*., 2005; Park *et al*., 2007). Fabric fiber surfaces with activated functional groups were used to conjugate with a variety of extracellular matrix components, namely gelatin, collagen, laminin and fibronectin (He *et al*., 2005, 2006; Baek *et al*., 2008; Koh *et al*., 2008). In dense fabric meshes or nonwoven fabrics, conjugation was only limited to surfaces

© Woodhead Publishing Limited, 2011



7.4 Schematics of various bioconjugation processes to achieve bioactive fabric surfaces during (a) plasma/wet chemical treatment, (b) surface grafts copolymerization and (c) co-spinning. The choice of each method depends on the nature of the fabric, bioactive molecule and fabric thickness. (Reproduced with permission from © Elsevier 2009, figure is adapted from Yoo *et al.*, 2009.)

as plasma could not penetrate deep inside the bulk of the fabrics. Bioconjugation of dense fabrics can be effectively accomplished via partial surface hydrolysis (Croll *et al*., 2004; Sun and Onneby, 2006; Zhu *et al*., 2002).

Graft copolymerization is another attractive technique to conjugate bioactive molecules on the fabric surface. Bioactive molecules are grafted on the fabric surfaces mediated though free radicals that are created by radiation or chemicals. Sulfonic acid groups were introduced on to nonwoven fabrics of polyethylene by radiation-induced graft polymerization of methacrylate and subsequent ring opening with sodium sulfite (Kim and Saito, 1999). These sulfonic functionalities were used to conjugate with silver ions in an effort to create antibacterial fabrics. Yao and co-researchers treated polyurethane (PU) nanofiber fabrics with argon plasma to introduce oxide and peroxide groups (Yao *et al*., 2008). These fabrics were dip-coated with 4-vinylpyridine and polymerization was mediated through

© Woodhead Publishing Limited, 2011

ultraviolet radiation to obtain PU-grafted poly(4-vinylpyridine). Antibacterial PU nanofiber surfaces were created by introducing pyridine quaternary slats with hexyl bromide. Using a similar conjugation approach Chen and co-workers created smart fabrics that responded to temperature changes by grafting poly(*N*-isopropylacryl amide) on to nonwoven PE fabric surfaces. These smart fabrics are extensively used in variety of biomedical applications where a change in external temperature causes the textile to respond and release bioactive agents (Chen *et al*., 2002). Further, similar approaches have been used to introduce variety of functional groups on the fibers of the fabrics that were utilized to conjugate with ECM components or drugs to improve their biological performance (Ma *et al*., 2005).

Co-spinning is another approach where functional groups are introduced on the fiber surface via co-spinning of different polymers containing varied functionalities in their structure as depicted in Fig. 7.4. It is important to obtain a homogenous polymer blend solution prior to co-spinning to achieve reproducible results.

7.3.4 Inclusion complexes

Inclusion complexes utilize the principle of attaching small molecules in the molecular cavity of large molecules. Cyclodextrin is a most commonly used large molecule to produce inclusion complexes in textiles and other pharmaceutical formulations (Davis and Brewster, 2004). Cyclodextrins present unique hydrophobic interior and hydrophilic exterior surfaces that make them an attractive choice to produce hydrophobic complexation drug formulations. Cyclodextrins were immobilized on the fiber surface via the aforementioned bioconjugation processes. Antibiotic drug immobilized polyamide fibers were produced by coating with a cyclodextrin–ciprofloxacin inclusion complex (Ghoul *et al*., 2008). Efforts were made to directly attach hydrophobic cyclodextrin component on to nanofibers (Buschmann *et al*., 2001) while exposing hydrophilic groups on the surface to produce drug complexes. A grafting technique was adopted to introduce cyclodextrin on to polyamide and polyurethane fabric surfaces to produce drug inclusion complexes (Nichifor *et al*., 2009). Efforts were also made to introduce cyclodextrin derivatives on the fabric surfaces to produce inclusion complexes (Buschmann *et al*., 2001). Several other large molecules, such as fullerene, aza-crown ether and their derivatives, have also been attempted to produce inclusion complexes (Breteler *et al*., 2002).

7.3.5 Ion complexes

Drugs can also be attached to fabric surfaces making use of charges present on both the fiber surfaces and drugs producing an ion complex of neutral charge. In such complexes drug elution is controlled by the ability of the fabric surface to preferentially exchange counter-ions (Jaskari *et al*., 2001). In these systems, drug molecules act as mobile counter-ions and are released in exchange for ions in the

© Woodhead Publishing Limited, 2011

physiological system. Ion exchange polymers or polymers impregnated with ion exchange groups are popular choice for such applications. Fabrics produced from such polymers are incubated in an ionic drug or bioactive molecule solution to produce ion complexation. Liao and co-workers (Liao *et al*., 2005) used chitosan–alginate blends to produce fibers with charged surfaces and successfully produced drug complexation. A variety of bioactive molecules, such as dexamethasone, BSA, growth factor (PDGF-bb) and avidin, were mixed with either chitosan or alginate solution to produce drug loaded fabrics. Positively charged molecules like PDGF-bb and avidin are preferred to be incorporated into polymer solution which has abundance of positive charge such as chitosan. Drug–chitosan solution was drawn against alginate solution to produce drug loaded poly-ion complex fibers. In contrast, mixing positively charged drug molecules with ionizable negative ions forms aggregates such as alginate–drug aggregates that fail to form fiber structures. Negatively charged molecules like BSA and FITC-BSA are preferred for mixing with alginate and drawn against chitosan solution to produce drug loaded fibers. Using the ion complexation principle Yao *et al*. produced gastro-mucoadhesive delivery system in which poly(ethylene-*g*-styrenetrimethyl-ammonium-chloride) anion ion-exchange fabrics were loaded with furosemide (Yao *et al*., 2008b). Using a similar approach, Kim and Saito attached silver ions on to nonwoven fabrics utilizing sulfonic acid functionalities on the surface to create antibacterial fabrics (Kim and Saito, 1999). Ion complexation is a very simple and convenient way to load only charged bioactive molecules and drugs on the fabrics with charged functionalities. Drug release can be altered by modulating the type and concentration of surface ion exchange groups.

7.3.6 Characterization of drug-loaded textiles

Bioactive medical textiles are characterized for their morphology, mechanical properties, degradation, drug loading efficiency and release using variety of analytical techniques, *in vitro* and *in vivo* models during their development.

Fabric surface morphology is characterized using microscopic techniques including optical microscopy, scanning electron microscopy (SEM) and atomic force microscopy (AFM). Fabric surface images provide useful information including textile nature, fiber diameter, deformities and degradation (Brewster *et al*., 2004; He *et al*., 2008). Morphological investigations can also be used to study cell viability and spreading. Using SEM analysis Kumbar *et al*. visually showed fiber diameter dependent cell behavior (Kumbar *et al*., 2008).

Thermogravimetric analysis (TGA) and differential scanning calorimetric (DSC) analysis are used to determine the physical form of the encapsulated drug (Brewster *et al*., 2004; He *et al*., 2008). The physical form of the encapsulated drug is an important factor in determining drug release kinetics. For instance, highly crystalline drugs take longer to release the encapsulated drug than their amorphous state.

© Woodhead Publishing Limited, 2011

Mechanical testing of the medicated textiles is highly desirable to determine the suitability of end application. Good mechanical stability is required to withstand original shape and size for the applications where repeated stretch and release is involved. Bioactive medical textiles should possess adequate mechanical properties to support the repair and regeneration of organs or tissues in regenerative medicine applications (Kumbar *et al*., 2008).

Fabric degradation behavior and pattern provide valuable information on drug release behavior and *in vivo* performance. Degradation studies are usually carried out in simulated body fluids (SBF) at physiological temperature. To simulate *in vivo* conditions enzyme can also be added to SBF. A known weight of fabric is incubated in degradation media and changes in morphology, mechanical strength and molecular weight changes are followed at different time intervals to determine extent of *in vitro* degradation (Cui *et al*., 2006).

Drug loading efficiency can be determined by extracting the drug using solvents followed by quantification. *In vitro* release of bioactive agents can be carried out in SBF such as phosphate buffered saline (PBS) at 37°C and the released drug can be quantified using a suitable analytical method. In brief, known weights of medicated textiles are suspended in dissolution media such as PBS under constant agitation. Periodically, known quantities of dissolution media are withdrawn and analyzed for drug content using analytical techniques such as high performance liquid chromatography (HPLC), gel permeation chromatography (GPC), calorimetric and mass spectroscopy methods. Choice of suitable analytical technique for quantification depends on various factors including drug nature, molecular weight, stability, convenience and level of accuracy. Medicated textiles for transdermal applications utilize Franz type diffusion cells (Kreilgaard *et al*., 2000; Romonchuk and Bunge 2010) to study *in vitro* drug release behavior. Alternatively, paddle over disc assembly (Mittal *et al*., 2009) and rotating cylinder (Verreck *et al*., 2003b) type diffusion cells are also popularly used to study *in vitro* drug release.

The ultimate performance of medicated bioactive fabrics is carried out using suitable *in vitro* cell culture conditions or *in vivo* animal models. The efficacy of bioactive fabrics can be determined by evaluating the samples at different time intervals using various techniques, including histology.

7.4 Applications of drug-releasing textiles

Due to high surface area and simple drug incorporation process, textiles have been very popular choice for controlled drug delivery applications. Medicated textile based products have been designed for wound care, deliver drugs across skin (transdermal delivery), anti-fungal/anti-microbial barriers, anticancer drug and ophthalmic drug carriers. The following section discusses a few examples of medicated textiles for different applications.

© Woodhead Publishing Limited, 2011

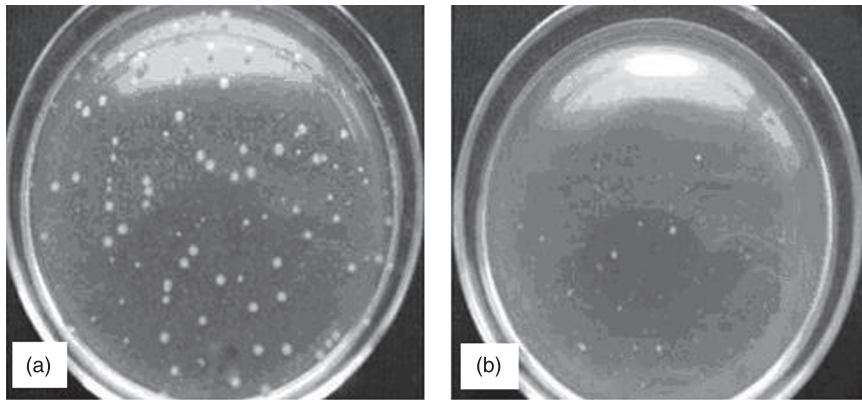
7.4.1 Drug-releasing textiles in wound care

Controlled water vapor transport and oxygen permeability are the essential requirements to promote wound healing. Along with these properties, the ideal wound dressing material should also possess excellent resistance to the penetration of microorganisms. In the case of chronic wounds, it is necessary to treat with antibiotics to eliminate possible infections. Both woven and nonwoven textiles present very small pore size to allow controlled fluid transport and resist infiltration of infectious microorganisms. In recent years medicated electrospun nonwoven fabrics of both degradables and non-degradables have been developed as wound dressings (Katti *et al*., 2004; Kenawy *et al*., 2002; Kim *et al*., 2003, 2004; Zong *et al*., 2004; Ghoul *et al*., 2008; Wang *et al*., 2009; Williamson *et al*., 2004; Wollina *et al*., 2003). Kenawy *et al*. fabricated electrospun fabrics from non-degradable polymer, poly(ethylene-*co*-vinyl acetate) (PEVA), a biodegradable polymer poly(lactic acid) (PLA) and a 50:50 blend of PEVA and PLA for the release of tetracycline hydrochloride (Kenawy *et al*. 2002). The electrospun PEVA matrices showed faster release kinetics compared to electrospun PLA and blend matrices. Burst release followed by a slower release was exhibited. Tetracycline release rate from blend fabrics was intermediate in-between that of PEVA and PLA, which shows the possibility of controlling release rate by varying the matrix polymer. Antibiotic nonwoven fabrics of PLAGA and their poly(ethylene glycol) based copolymers could retain the activity of encapsulated Mefoxin® and successfully inhibit the growth of *Staphylococcus aureus in vitro* and promote wound healing *in vivo* in a rat model (Kim *et al*., 2004; Zong *et al*., 2004). Antibacterial fabrics of cyclodextrin decorated polyamide could retain the activity of encapsulated ciprofloxacin and found to be effective against *Staphylococcus aureus*, *Staphylococcus epidermidis* and *Escherichia coli* (Ghoul *et al*., 2008). Cyclodextrins were fixed on to polyamide (PA) fibers, using citric acid as the cross-linking agent. Ciprofloxacin–cyclodextrin complexes attached to polyamide fabric surfaces showed enhanced anti-bacterial activity compared to neat drug due to increased surface area.

Anti-bacterial wool fabrics were produced by covalent immobilization of lysozyme via the gluteraldehyde reaction (Wang *et al*., 2009). Dynamic culture conditions such as shake flask tests showed higher bacterial inhibition rate over plain wool fabrics as shown in Fig. 7.5. Covalent lysozyme attachment was durable and retained 43% of lysozyme activity even after five cycles of washing. Such anti-bacterial textiles are attractive in fabricating external medical products that can avoid infection.

Ovalbumin loaded PCL nonwoven fabrics released 60% of the protein load in 2 days while fabrics loaded with ovalbumin nanoparticles could sustain the release up to 14 days (Williamson *et al*., 2004). This study demonstrated the ability to deliver multiple factors both faster and slower rates to influence specific wound healing stages.

© Woodhead Publishing Limited, 2011



7.5 Antibacterial effects of wool fabrics for (a) an untreated wool fabric, and (b) a lysozyme immobilized wool fabric. Bacteriostasis to *Staphylococcus aureus* was up to 81% for the lysozyme immobilized fabric. (Reproduced with permission from © Springer 2009, figure is adapted from Wang *et al.*, 2009.)

7.4.2 Drug-releasing textiles in topical/transdermal drug delivery

Transdermal/topical drug delivery routes are attractive since they minimize required drug dosage and non specific site toxicity. Several woven and nonwoven fabrics have been developed to deliver bioactive agents to treat various ailments. Itraconazole medicated fabrics were developed to treat fungal infection (Brewster *et al*., 2004; Verreck *et al*., 2003a,b), while itraconazole release from the polyurethane (SPU) samples was dependent on the drug loading and the fiber diameter. Diffusion of itraconazole from SPU followed Fickian kinetics without initial burst release of the drug at lower drug loadings (Verreck *et al*., 2003a,b). Itraconazole formulations in a water soluble polymer hydroxylpropyl methylcellulose (HPMC) were also developed by electrospinning (Verreck *et al*., 2003a,b). It was possible to influence the release profile of a water insoluble drug in aqueous environment by varying different parameters such as drug/polymer ratio and the diameters of the fibers.

Antibiotic nonwoven fabrics of PLA and PCL containing their model drugs namely tetracycline and chlorotetracycline hydrochloride, and amphotericin B were fabricated from electrospinning (Buschle-Diller *et al*., 2007). Release of antibiotics was fast and nearly complete from PCL fabrics compared to PLA fabrics due to increased matrix crystallinity. These matrices were effective against both Gram positive and Gram negative bacteria and inhibited their growth.

Clinical studies have been reported on anti-bacterial textiles to treat atopic eczema (Gauger *et al*., 2003) and atopic dermatitis (Ricci *et al*., 2006) in children. Gauger *et al*. studied the efficacy of silver coated textile to treat atopic eczema by

© Woodhead Publishing Limited, 2011

covering flexures of the elbows of 15 patients diagnosed as having generalized or localized atopic eczema due to the colonization of *Staphylococcus aureus*. As a control one arm was covered with non-coated textile for seven days. The silver-coated textile site showed the lower local SCORAD (SCORing Atopic Dermatitis) at all time points compared to the non-coated one. A significant reduction in local SCORAD was seen on days 7 and 14. Medicated transdermal textile formulations could be an attractive and convenient method of delivering various drugs in children.

In another clinical study, alkoxysilane quaternary ammonium coated silk textile was used to treat atopic dermatitis (AD) in pediatric patients (Ricci *et al*., 2006). Each patient was treated with coated and non-coated silk fabric for seven days. Microbiological examinations were done with standard cultural swabs and by means of quantification of bacterial agents using agar plates at baseline, after one hour and after seven days. In both the covered areas significant decrease in 'local SCORAD' was observed after seven days when compared to values obtained at baseline showing no superiority of coated silk fabric over non-coated fabric.

Ibuprofen loaded PAN/PCL nonwoven fabrics could release the encapsulated drug over a period of 16 days at almost constant rate following a burst release of 15% initial drug (Yu *et al*., 2008). Cumulative ibuprofen release profile implies the suitability of this system to release pain medication. Such transdermal patches are highly desirable for effective pain management.

Poly(vinyl alcohol) (PVA) electrospun fabrics containing four types of non-steroidal anti-inflammatory drug – sodium salicylate (freely soluble in water), diclofenac sodium (sparingly soluble in water), naproxen and indomethacin (both insoluble in water) – were developed to treat inflammation (Taepaiboon *et al*., 2006). Release of nonsteroidal anti-inflammatory drugs (NSAIDs) was carried out in a Franz diffusion cell using pig skin and the drugs were released for 1440 min when electrospun PVA nanofibers were used. The authors also demonstrated the ability to alter the NSAID release rate via a cross-linking reaction, where cross-linking was inversely proportional to release rate (Taepaiboon *et al*., 2007a).

Meloxicam loaded electrospun PVA fabrics could release a three-fold greater amount of drug compared to PVA cast films (Ngawhirunpat *et al*., 2009) due to high surface area. Cellulose acetate (CA) nonwovens could successfully control the release of vitamins where in cast films resulted in the burst release of vitamins (Taepaiboon *et al*., 2007b). Further, electrospun gallic acid encapsulated PLLA matrices were also developed as anti-bacterial surfaces to avoid infection (Chuysinuan *et al*., 2009).

Nichifor and co-workers developed troxerutin (Trox) grafted polyamide (PA) fabrics via inclusion complex with β-cyclodextrin grafting for a possible application in the treatment of venous insufficiency, hemorrhoids and capillary fragility (Nichifor *et al*. 2009). *In vitro* release demonstrated the fast release of physically bound (90%) compared to chemically bound (15%) Trox over 24 hours. *In vivo* test studies carried out in Wistar adult male rats also presented similar results

© Woodhead Publishing Limited, 2011

as observed *in vitro*. Chemically bound Trox showed higher florescence intensity in all areas and is much higher with a maximum at 24–48 hours after administration.

7.4.3 Drug-releasing textiles in regenerative engineering

Both woven and nonwoven textiles have been widely researched as temporary tissue replacements called scaffolds to repair and regenerate tissues. Specifically, electrospun nonwoven fabrics have been used as biomimetic scaffolds to repair several soft tissues (Kumbar *et al*., 2008). Electrospun nonwoven fabrics show structural similarities to the natural extracellular matrix (ECM), characterized by ultrafine continuous fibers, high surface-to-volume ratio, porosity and variable pore-size distribution. It is well documented that several cellular activities such as adhesion, proliferation, migration, differentiation and cell shape are influenced by the ECM in which the cells reside. Thus nonwoven fabric matrices present interconnected highly porous structures to facilitate cellular migration and transport of nutrients, and metabolic wastes to allow the formation of new tissue (Kumbar *et al*., 2007a,b). Nonwoven fabrics with the ability to deliver bioactive agents including antibiotics, growth factors and several other chemotherapeutic drugs were proven to be beneficial to accelerate tissue generation. ECM-like environment combined with growth factors provides an ideal environment for progenitors to attach and populate on to the scaffold and differentiate into desired tissue. Greisler *et al*. (1996) created fibroblast growth factors (FGF) eluting dacron and poly(dioxanone) textile vascular grafts to promote endothelialization. In an effort to promote endothelialization and reduce thrombus formation, Bide *et al*. (2001) surface immobilized vascular endothelial growth factor (VEGF) and an anticoagulant R.Hirudin on to knitted polyester grafts.

FGF-2 growth factor eluting titanium (Ti) nonwoven fabrics coated with hydroxyapatite (HA) could enhance bone healing rate in rabbit calvarial defect compared to Ti fabrics and defect alone (Ichinohe *et al*., 2008). FGF-2 eluting Ti scaffolds induced significantly higher bone formation accompanied by osteoblasts, blood corpuscles, fibrous tissue, and bone marrow-like structures. Conjugated FGF-2 resulted in significantly higher bone formation due to the retention and controlled elution of factor for longer duration.

Efforts to promote osteogenesis (Nie *et al*., 2008; Li *et al*., 2006) and nerve regeneration (Yan *et al*., 2009) were made by incorporating growth factors such as bone morphogenetic protein (BMP-2) and nerve growth factors (NGF) onto nanofibers. Antibiotic eluting nonwoven fabrics are popularly used to avoid infection, overcome postsurgical adhesion problems and promote wound healing (Bolgen *et al*., 2007). Plenty of literature is available on the bioactive factor eluting nanofiber matrices for variety of biomedical applications and can be read elsewhere (Kumbar *et al*., 2006).

© Woodhead Publishing Limited, 2011

7.4.4 Drug-releasing textiles in miscellaneous drug delivery applications

Nonwoven fabric formulations of anticancer drug doxorubicin hydrochloride (Dox) were found to be effective against glioma cells (C6 cell lines) in culture (Xu *et al*., 2005). Further these nanofiber formulations released 1,3-bis(2-chloroethyl)-1-nitrosourea (BCNU) up to 72 hours and could inhibit 93% of C6 cell growth *in vitro* (Xu *et al*., 2006).

One way of improving hydrophobic drug water solubility is to prepare their nanosized formulations. Hydrophobic chemotherapeutic drugs such as paclitaxel and rifampin nonwoven fabric formulations were prepared to improve drug aqueous solubility (Zeng *et al*., 2003, 2005; Xie and Wang, 2006). These nanofiber formulations could release the hydrophobic drug at a constant rate following the highly desired zero order release pattern. The same nanofiber formulations rapidly released the encapsulated hydrophilic drug. Based on the nature of the drug it is required to select suitable polymer system, fiber diameter and loading concentration to achieve the desired release pattern. Temperature sensitive 'smart' nonwoven fabrics of poly(*N*-isopropylacrylamide)-*co*-polystyrene (PNIPAM-*co*-PS) could sustain the release of anticancer drug daunorubicin above its lower critical solution temperature (LCST). These formulations were found to be effective against drug-resistant leukemia K562 cells and significantly inhibited their growth compared to control daunorubicin drug (Song *et al*., 2008).

Several nonwoven formulations were prepared to improve drug solubility and hence bioavailability (Brewster *et al*., 2004; Yao *et al*., 2008a,b, 2009). Ion-exchange groups containing nonwoven fabric formulations were developed as gastro-mucoadhesive delivery systems to improve drug bioavailability of poorly water soluble drugs (Yao *et al*., 2008a,b). Nonwoven fabric formulations containing ophthalmic drugs could retain the drug concentrations for an extended period of time and improve the efficacy of contact lenses (Tauber *et al*., 2009). Nonwoven fabric formulations containing cold medications were effective in delivering the drug for prolonged periods of time (Weinforth *et al*., 2007).

7.5 Conclusions

In recent years significant research activity has been focused on the design and optimization of drug eluting fabrics for a variety of biomedical applications. Textile formulations significantly improve the aqueous solubility of poorly soluble drugs and have been designed for both systemic and topical administrations. More testing of drug eluting textiles in suitable animal models is needed to fine tune clinical efficacy. Textile based woven and nonwoven drug delivery systems present unique properties, including high surface area, and drug loading capacity, fabrication ease and options for surface modifications make them attractive alternatives to current drug delivery devices. Electrospun nonwoven fabrics,

© Woodhead Publishing Limited, 2011

composites of both woven and nonwoven biodegradable fabrics with the ability to deliver factors have attracted a great deal of attention as scaffolds in tissue engineering applications.

7.6 Future trends

Both woven and nonwoven textiles present morphological similarities to the natural ECM comprising of continuous fibers, high surface area and porosity. These remarkable surface properties make them attractive choice for several biomedical applications including drug delivery. The majority of literature reports primarily focused on optimizing the design parameters to encapsulate or covalently attach drugs to the fabric surfaces. Further drug eluting textile characterization was often limited to *in vitro* drug release and cellular response. However, the ultimate performance of medicated textiles has to be tested in suitable animal models. Drug eluting textiles often suffer from poor drug encapsulation efficiency and most of the drug will be released in early few hours due to high surface area. Future efforts need to focus on improving the drug encapsulation efficiency and sustaining the release for prolonged periods of time to meet the clinical needs. Although several alternative methods, including core-shell fiber design, covalent drug attachment and polymer–drug conjugates, have been proposed they often require complicated synthetic procedures and high availability of surface functionalities to aid covalent attachment. It is highly desirable to develop simple procedures and protocols to fabricate drug eluting textiles for commercial variability. Nonwoven drug eluting textiles fabricated from electrospinning utilizes several fluorinated and toxic organic solvents to dissolve polymers. Such toxic solvents might affect the structural conformation of several biopolymers and proteins and result in undesired cellular response. Therefore, in general, it is critical to replace toxic organic solvents with aqueous based or less toxic solvents as well as avoid use of elevated temperatures during drug loading. Future drug delivery systems can make use of nanosized implantable sensors to modulate the release of bioactive agents from these textiles. For instance, drug delivery textile can employ glucose sensor to monitor glucose level and could enzymatically or by some other physical means release encapsulated insulin to treat diabetes-like chronic disease. Physiologically responsive polymers can be used to design 'smart' chemotherapeutic agent eluting textiles to treat cancer tissues locally. Drug release can be programmed based on the tumor microenvironment.

Textiles due to the ECM structural similarity have been known to influence cell attachment, proliferation and differentiation for tissue engineering applications. However, these fabrics could mimic the mechanical properties close to native tissue that has to be generated. Efforts are being made to improve mechanical properties of electrospun nanofibers to match the native tissue by a combination of several polymers, fiber diameter and fiber orientation. Efforts have to be made

© Woodhead Publishing Limited, 2011

to improve the encapsulation efficiency as well as retention of bioactivity of growth factors and proteins to achieve better tissue regeneration. Also more efforts need to be made to improve efficiency of medicated textile production, packing, shipping and handling. Such efforts can further improve the efficacy of medicated textiles, and can lead to the development of commercially viable technology for a variety of biomedical applications.

7.7 Acknowledgments

This work was supported by NIH RO1 EB004051, AR052536, and NSF EFRI-0736002. Dr Laurencin was the recipient of Presidential Faculty Fellow Award from the National Science Foundation.

7.8 Sources of further information and advice

Ignatious F, Sun L, Lee C-P and Baldoni J (2010). Electrospun nanofibers in oral drug delivery, *Pharm Res*, 27, 576–588.

Kumbar S G, Nair L S, Bhattacharya S and Laurencin C T (2006). Polymeric nanofibers as novel carriers for the delivery of therapeutic molecules, *J Nanosci Nanotechnol*, 6, 2691–2607.

Nierstrasz V A (2007). Textile-based drug release systems, in *Smart Textiles for Medicine and Healthcare: Materials, Systems and Applications*, Langenhove L V (ed.), Woodhead Textiles Series No. 63, Woodhead Publishing, Cambridge, UK.

Sill T J, von Recum H A (2008), Electrospinning: applications in drug delivery and tissue engineering, *Biomaterials*, 29, 1989–2006.

Wollinaa U, Heide M, Müller-Litz W, Obenauf D and Ash J (2003). Functional textiles in prevention of chronic wounds,wound healing and tissue engineering, in Elsner P, Hatch K, Wigger-Alberti W (eds), *Textiles and the Skin. Current Problems in Dermatology*, Karger, Basel, 31, pp. 82–97.

Yoo H S, Kim T G and Park T G (2009). Surface-functionalized electrospun nanofibers for tissue engineering and drug delivery, *Adv Drug Delivery Rev* 61, 1033–1042.

7.9 References

Baek H S, Park Y H, Ki C S, Park J C and Rah D K (2008). Enhanced chondrogenic responses of articular chondrocytes onto porous silk fibroin scaffolds treated with microwave-induced argon plasma, *Surf Coat Technol*, 202, 5794–5797.

Benson H A E (2005). Transdermal drug delivery: penetration enhancement techniques, *Curr Drug Delivery*, 2, 23–33.

Bide M J, Phaneuf M D, LoGerfo F V, Quist W C and Szycher M (2001). Arterial grafts as biomedical textiles. In: *Bioactive Fibres And Polymers*, Edwards J V and Vigo T L (eds.), American Chemical Society, pp. 125–154.

Blom A, Estela C, Bowker K, MacGowan A and Hardy J R (2000). The passage of bacteria through surgical drapes, *Ann R Coll Surg Engl*, 82, 405–407.

Bolgen N, Vargel I, Korkusuz P, Menceloglu Y Z and Piskin E (2007). *In vivo* performance of antibiotic embedded electrospun PCL membranes for prevention of abdominal adhesions, *J Biomed Mater Res B: Appl Biomater*, 81(2), 530–543.

© Woodhead Publishing Limited, 2011

Brewster M E, Verreck G, Chun I, Rosenblatt J, Mensch J, *et al.* (2004). The use of polymer-based electrospun nanofibers containing amorphous drug dispersions for the delivery of poorly water-soluble pharmaceuticals, *Pharmazie*, 59, 387–391.

Buschle-Diller G, Cooper J, Xie Z, Wu Y, Waldrup J, *et al.* (2007). Release of antibiotics from electrospun bicomponent fibers, *Cellulose* 14, 553–562.

Buschmann H-J, Knittel D and Schollmeyer E (2001). New textile applications of cyclodextrins. *J Incl Phenom Macrocyclic Chem*, 40, 169–172.

Chen K S, Tsai J C and Chou C W (2002). Effects of additives on the photo-induced grafting polymerization of *N*-isopropylacrylamide gel onto PET film and PP nonwoven fabric surface, *Mater Sci Eng C*, 20, 203–208.

Chew S Y, Wen J, Yim E K and Leong K W (2005). Sustained release of proteins from electrospun biodegradable fibers, *Biomacromolecules*, 6, 2017–2024.

Chuysinuan P, Chimnoi N, Techasakul S and Supaphol P (2009). Gallic acid-loaded electrospun poly(L-lactic acid) fiber mats and their release characteristic, *Macromol. Chem. Phys*, 210, 814–822.

Constantinides P P (1995). Lipid microemulsions for improving drug dissolution and oral absorption: physical and biopharmaceutical aspects, *Pharm Res*, 12, 1561–1572.

Croll T I, O'Connor A J, Stevens G W and Cooper-White J J (2004). Controllable surface modification of poly(lactic-co-glycolic acid) (PLGA) by hydrolysis or aminolysis I: Physical, chemical, and theoretical aspects, *Biomacromolecules*, 5, 463–473.

Cui W, Li X, Zhu X, Yu G, Zhou S, *et al.* (2006). Investigation of drug release and matrix degradation of electrospun poly(DL-lactide) fibers with paracetanol inoculation, *Biomacromolecules*, 7, 1623–1629.

Davis M E and Brewster M E (2004). Cyclodextrin-based pharmaceutics: past, present and future, *Nat Rev Drug Discovery*, 3, 1023–1035.

Davis S S (2004). Coming of age of lipid-based drug delivery systems, *Adv Drug Delivery Rev*, 56, 1241–1242.

Ding B S, Dziubla T, Shuvaev V V, Muro S and Muzykantov V R (2006). Advanced drug delivery systems that target the vascular endothelium, *Mol Intervent*, 6(2), 98–112.

Dubas S T, Kumlangdudsana P and Potiyaraj P (2006). Layer-by-layer deposition of antimicrobial silver nanoparticles on textile fibers, *Colloids Surf A:* 289, 105–109.

Duncan R (2003). The dawning era of polymer therapeutics, *Nat Rev Drug Discovery*, 2(5), 347–360.

Francis M F, Cristea M and Winnik F M (2004). Polymeric micelles for oral drug delivery: Why and how, *Pure Appl Chem*, 76(7–8), 1321–1335.

Frenot A and Chronakis I S (2003). Polymer nanofibers assembled by electrospinning, *Curr Opin Colloid Interface Sci*, 8, 64–75.

Gauger A, Mempel M, Schekatz A, Schafer T, Ring, *et al.* (2003). Silver-coated textiles reduce *Staphylococcus aureus* colonization in patients with atopic eczema, *Dermatology*, 207, 15–21.

Ghoul Y E, Blanchemain N, Laurent C, Campagne C, Achari E L, *et al.* (2008). Chemical, biological and microbiological evaluation of cyclodextrin finished polyamide inguinal meshes, *Acta Biomater*, 4, 1392–1400.

Goldberg M and Gomez-Orellana I (2003). Challenges for the oral delivery of macromolecules, *Nat Rev Drug Discovery*, 2, 289–295.

Greco F and Vicent M J (2008). Polymer–drug conjugates: current status and future trends, *Front Biosci*, 13, 2744–2756.

Greisler H P, Gosselin C, Ren D, Kang S S and Du K, (1996). Bioactive polymers and tissue engineered blood vessels, *Biomaterials,* 17, 329–336.

© Woodhead Publishing Limited, 2011

He C L, Huang Z M and Han X J (2008). Fabrication of drug-loaded electrospun aligned fibrous threads for suture applications, *J Biomed Mater Res A*, 89A, 80–95.

He W, Ma Z W, Yong T, Teo W E and Ramakrishna S (2005). Fabrication of collagen-coated biodegradable polymer nanofiber mesh and its potential for endothelial cells growth, *Biomaterials*, 26, 7606–7615.

He W, Yong T, Ma Z W, Inai R, Teo W E, *et al*. (2006). Biodegradable polymer nanofiber mesh to maintain functions of endothelial cells, *Tissue Eng*, 12, 2457–2466.

Hou Q, Maria C, Walsh R F, John J A B, Howdle S M, *et al*. (2006). Incorporation of proteins within alginate fibre-based scaffolds using a post-fabrication entrapment method, *J Pharm Pharmacol*, 58(7), 895–902

Hwang C M, Khademhosseini A, Park Y, Sun K and Lee S H (2008). Microfluidic chip-based fabrication of PLGA microfiber scaffolds for tissue engineering, *Langmuir*, 24(13), 6845–6851.

Ichinohe N, Kuboki Y and Tabata Y (2008). Bone regeneration using titanium nonwoven fabrics combined with FGF-2 release from gelatin hydrogel microspheres in rabbit skull defects, *Tissue Eng A*, 14(10), 1663–1671.

Järvinen T and Savolainen J (2008). Prodrugs: design and clinical applications, *Nat Rev Drug Discovery*, 7, 255–270.

Jaskari T, Vuorio M, Kontturi K, Manzanares J A and Hirvonen J (2001). Ion exchange fibers an drugs: an equilibrium study, *J Controlled Release*, 70, 219–229.

Jayaraman K, Kotaki M, Zhang Y, Mo X and Ramakrishna S (2004). Recent advances in polymer nanofibers, *J Nanosci Nanotechnol*, 4, 52–65.

Jun Y J, Min J H, Jida E, Yoo J H, Kim J H, *et al*. (2008). A micellar prodrug of paclitaxel conjugated to cyclotriphosphazene, *Bioorg Med Chem Lett*, 18, 6410–6413.

Kabanov A V and Vinogradov S V (2009). Nanogels as pharmaceutical carriers: finite networks of infinite capabilities, *Angew Chem Int Ed Engl*, 48(30), 5418–5429.

Katti D S, Robinson K W, Ko F K and Laurencin C T (2004). Bioresorbable nanofiber-based systems for wound healing and drug delivery: Optimization of fabrication parameters, *J Biomed Mater Res B*, 70, 286–296.

Kenawy E R, Bowlin G L, Mansfield K, Layman J, Simpson D G, *et al*. (2002). Release of tetracycline hydrochloride from electrospun poly(ethylene-*co*-vinylacetate), poly(lactic acid), and a blend, *J Controlled Release*, 81, 57–64.

Kim K, Chang C, Zong X, Fang D, Hsiao B S, *et al*. (2003). Incorporation of an antibiotic drug in electrospun poly(lactide-*co*-glycolid) non-woven nanofiber scaffold, *Polym Prepri*, 44, 98.

Kim K, Luu Y K, Chang C, Fang D, Hsiao B S, *et al*. (2004). Incorporation and controlled release of a hydrophilic antibiotic using poly(lactide-*co*-glycolide)-based electrospun nanofibrous scaffolds, *J Controlled Release*, 98, 47–56.

Kim M and Saito K (1999). Preparation of silver-ion-loaded nonwoven fabric by radiation-induced graft polymerization, *React Funct Polym*, 40, 275–279.

Kim T G, Lee D S and Park T G (2007). Controlled protein release from electrospun biodegradable fiber mesh composed of poly(epsilon-caprolactone) and poly(ethylene oxide), *Int J Pharm*, 338, 276–283.

Klueh U, Wagner V, Kelly S, Johnson A and Bryers J D (2000). Efficacy of silver-coated fabric to prevent bacterial colonization and subsequent device-based infection, *J Biomed Mater Res* (*Appl Biomater*), 53, 621–631.

Koh H S, Yong T, Chan C K and Ramakrishna S (2008). Enhancement of neurite outgrowth using nano-structured scaffolds coupled with laminin, *Biomaterials*, 29, 3574–3582.

© Woodhead Publishing Limited, 2011

Kreilgaard M, Pedersen E J and Jaroszewski J W (2000). NMR characterisation and transdermal drug delivery potential of microemulsion systems, *J Controlled Release*, 69, 421–433.

Kumbar S G, Bhattacharyya S, Swaminathan S and Laurencin C T (2007a). A preliminary report on a novel electrospray technique for nanoparticle based biomedical implants coating: Precision electrospraying, *J Biomed Mater Res Part B*, 81(1), 91–103.

Kumbar S G, Kofron M D, Nair L S and Laurencin C T (2007b). Cell behavior toward nanostructured surfaces, in *Biomedical Nanostructure*, Gonsalves K E, Halberstadt C R, Laurencin C T and Nair L S (eds.), John Wiley and Sons, pp. 261–295.

Kumbar S G, Nair L S, Bhattacharya S, and Laurencin C T (2006). Polymeric nanofibers as novel carriers for the delivery of therapeutic molecules, *J Nanosci Nanotechnol*, 6, 2691–2607.

Kumbar S G, Nukavarapu S, James R, Nair L S and Laurencin C T (2008). Electrospun poly(lactic acid-*co*-glycolic acid) scaffolds for skin tissue engineering, *Biomaterials*, 29(30), 4100–4107.

Li C, Vepari C and Jin H J (2006). Electrospun silk-BMP-2 scaffolds for bone tissue engineering, *Biomaterials*, 27, 3115–3124.

Liao C I, Wan A C A, Yim E K F and Leong K W (2005). Controlled release from fibers of polyelectrolyte complexes, *J Controlled Release*, 104, 347–358.

Low P S and Antony A C (2004). Folate receptor-targeted drugs for cancer and inflammatory diseases, *Adv Drug Delivery Rev*, 56(8), 1055–1058.

Ma Z H, Yu D G, White C J B, Hua L N, Zai X F and Li M Z (2009). Microencapsulation of tamoxifen: Application to cotton fabric, *Colloids Surf B:* 69, 85–90.

Ma Z W, Kotaki M, Yong T, He W and Ramakrishna S (2005). Surface engineering of electrospun polyethylene terephthalate (PET) nanofibers towards development of a new material for blood vessel engineering, *Biomaterials*, 26, 2527–2536.

Maestrelli F, Cirri C, Corti G, Mennini N and Mura P (2008). Development of enteric-coated calcium pectinate microspheres intended for colonic drug delivery, *Eur J Pharm Biopharm*, 69, 508–518.

Marimuthu M and Kim S (2010). Spontaneous extrusion of porous amphiphilic triblock copolymeric microfibers under microfluidic conditions, *Polym J*, 42, 100–102.

Mittal A, Sar U V S and Ali A (2009). Formulation and evaluation of monolithic matrix polymer films for transdermal delivery of nitrendipine, *Acta Pharm*, 59, 383–393.

Nelson G (2002). Application of microencapsulation in textiles, *Int J Pharm*, 242(1–2), 55–62.

Ngawhirunpat T, Opanasopit P, Rojanarata T and Akkaramongkolporn P (2009). Development of meloxicam-loaded electrospun polyvinyl alcohol mats as a transdermal therapeutic agent, *Pharm Dev Technol*, 14, 73–82.

Nichifor M, Constantin M, Mocanu G, Fundueanu G, Branisteanu D, *et al.* (2009). New multifunctional textile biomaterials for the treatment of leg venous insufficiency, *J Mater Sci: Mater Med*, 20, 975–982.

Nie H, Soh B W, Fu Y C and Wang C H (2008). Three-dimensional fibrous PLGA/Hap composite scaffold for BMP-2 delivery, *Biotechnol Bioeng*, 99, 223–234.

Ohshima Y, Nishino K, Yonekura Y, Kishimoto S and Wakabayashi S (1987). Clinical application of chitin non-woven fabric as wound dressing, *Eur J Plastic Surg*, 10, 66–69.

Park H, Lee K Y, Lee S J, Park K E and Park W H (2007). Plasma-treated poly(lactic-coglycolic acid) nanofibers for tissue engineering, *Micromol Res*, 15, 238–243.

© Woodhead Publishing Limited, 2011

Park K (1998). *Controlled Drug Delivery: Challenges and Strategies*, American Chemical Society.

Peppas L B (1997). Polymers in controlled drug delivery, *Med Plastics Biomater*, 34. Available: http://www.devicelink.com/mpb/archive/97/11/003.html.

Perelshtein I, Applerot G, Perkas N, Guibert G, Mikhailov S, *et al.* (2008). A sonochemical coating of silver nanoparticles on textile fabrics (nylon, polyester and cotton) and their anti-bacterial activity, *Nanotechnology*, 19, 245705–245711.

Pornsopone V, Supaphol P, Rangkupan R, and Tantayanon S (2007). Electrospun methacrylate-based copolymer/indomethacin fibers and their release characteristics of indomethacin, *J Polym Res*, 14, 53–59.

Prausnitz M R, Mitragotri S and Langer R (2004). Current status and future potential of transdermal drug delivery, *Nat Rev Drug Discovery*, 3(2), 115–124.

Ranade V V and Hollinger M A (2004). *Drug Delivery Systems*, 2nd edition, CRC Press, London.

Ricci G, Patrizi A, Mandrioli P, *et al.* (2006). Evaluation of the antibacterial activity of a special silk textile in the treatment of atopic dermalitis, *Dermatology*, 213, 224–227.

Romonchuk W J and Bunge A L (2010). Mechanism of enhanced dermal permeation of 4-cyanophenol and methyl paraben from saturated aqueous solutions containing both solutes, *Skin Pharmacol Physiol*, 23, 152–163.

Saad M, Garbuzenko O B, Ber E, Chandna P, Khandare J J, *et al.* (2008). Receptor targeted polymers, dendrimers, liposomes: Which nanocarrier is the most efficient for tumor-specific treatment and imaging?, *J Controlled Release*, 130(2), 107–114.

Song M, Guo D, Pan C, Jiang H, Chen C, *et al.* (2008). The application of poly(*N*-isopropylacrylamide)-*co*-polystyrene nanofibers as an additive agent to facilitate the cellular uptake of an anticancer drug, *Nanotechnology*, 19, 165102.

Stella V J and Nti-Addae K W (2007). Prodrug strategies to overcome poor water solubility, *Adv Drug Delivery Rev*, 59(7), 677–694.

Sun H and Onneby S (2006). Facile polyester surface functionalization via hydrolysis and cell-recognizing peptide attachment, *Polym Int*, 55, 1336–1340.

Taepaiboon P, Rungsardthong U and Supaphol P (2006). Drug-loaded electrospun mats of poly(vinyl alcohol) fibres and their release characteristics of four model drugs, *Nanotechnology*, 17, 2317–2329.

Taepaiboon P, Rungsardthong U and Supaphol P (2007a). Vitamin-loaded electrospun cellulose acetate nanofiber mats as transdermal and dermal therapeutic agents of vitamin A acid and vitamin E, *Eur J Pharm Biopharm*, 67, 387–397.

Taepaiboon P, Rungsardthong U and Supaphol P (2007b). Effect of cross-linking on properties and release characteristics of sodium salicylate-loaded electrospun poly(vinyl alcohol) fibre mats, *Nanotechnology*, 18, 175102.

Tauber S, Fuerst R, Davis K, Bowman L, Wnek G, *et al.* (2009). Drug delivery system and methods of use, U.S. Patent Application 20090269392.

ten Breteler M R, Nierstrasz V A and Warmoeskerken M M C G (2002). Textile slow-release systems with medical applications, *AUTEX Res J*, 2, 175–189.

Theron S A, Zussman E, and Yarin A L (2004). Experimental investigation of the governing parameters in the electrospinning of polymer solutions, *Polymer*, 45, 2017–2030.

Torchilin V P and Lukyanov A N (2003). Peptide and protein drug delivery to and into tumors: challenges and solutions, *Drug Discovery Today*, 8, 259–266.

Verreck G, Chun I, Rosenblatt J, Peetersa J, Dijcka A V, *et al.* (2003a). Incorporation of drugs in an amorphous state into electrospun nanofibers composed of a water-insoluble, nonbiodegradable polymer, *J Controlled Release*, 92, 349–360.

© Woodhead Publishing Limited, 2011

Verreck G, Chun I, Peeters J, Rosenblatt J and Brewster M E (2003b). Preparation and characterization of nanofibers containing amorphous drug dispersions generated by electrostatic spinning, *Pharm Res*, 20, 810–817.

Wang Q, Fan X, Hu Y, Yuan J, Cui L and Wang P (2009). Antibacterial functionalization of wool fabric via immobilizing lysozymes, *Bioprocess Biosyst Eng*, 32, 633–639.

Watts P J, and Illum L (1997). Colonic drug delivery, *Drug Dev. Ind. Pharm.*, 23, 893–913.

Wienforth F, Landrock A, Schindler C, Siegert J and Kirch W (2007). Smart textiles: A new drug delivery system for symptomatic treatment of a common cold, *J Clin Pharmacol*, 47, 653–659.

Williamson M R, Chang H I and Coombes A G A (2004). Gravity spun polycaprolactone fibres: controlling release of a hydrophilic macromolecule (ovalbumin) and a lipophilic drug (progesterone), *Biomaterials*, 25, 5053–5060.

Wollinaa U, Heide M, Müller-Litz W, Obenauf D and Ash J (2003). Functional textiles in prevention of chronic wounds, wound healing and tissue engineering, in *Textiles and the Skin. Current Problems in Dermatology*, Elsner P, Hatch K and Wigger-Alberti W (eds.), Karger: Basel, 31, pp. 82–97.

Whyte W, Hodgson R, Bailey P V and Graham J (2005). The reduction of bacteria in the operation room through the use of non-woven clothing, *Br J Surg*, 65, 469–474.

Xie J W and Wang C H (2006). Electrospun micro- and nanofibers for sustained delivery of paclitaxel to treat C6 glioma in vitro, *Pharm Res*, 23, 1817–1826.

Xu X, Chen X, Xu X, Lu T, Wang X, *et al.* (2006). BCNU-loaded PEGPLLA ultrafine fibers and their in vitro antitumor activity against glioma C6 cells, *J Control Release*, 114, 307–316.

Xu X, Yang L, Xu X, Wang X, Chen X, *et al.* (2005). Ultrafine medicated fibers electrospun from W/O emulsions, *J Controlled Release*, 108, 33–42.

Yan S, Xiaoqiang L, Lianjiang T, Chen H and Mo Xiumei (2009). Poly(L-lactide-co-3-caprolactone) electrospun nanofibers for encapsulating and sustained releasing proteins, *Polymer*, 50, 4212–4219.

Yao C, Li X S, Neoh K G, Shi Z L and Kang E T (2008a). Surface modification and antibacterial activity of electrospun polyurethane fibrous membranes with quaternary ammonium moieties, *J Membr Sci*, 320, 259–267.

Yao H, Wang S, Sun Y, Liu H and Li S (2009). *In vivo* assessment of novel furosemide gastro-mucoadhesive delivery system based on a kind of anion ion-exchange fiber, *Drug Dev Ind Pharm*, 35, 548–554.

Yao H, Xu L, Han F, Che X, Dong Y, *et al.* (2008b). A novel riboflavin gastro-mucoadhesive delivery system based on ion-exchange fiber, *Int J Pharm*, 364, 21–26.

Yoo H S, Kim T G and Park T G (2009). Surface-functionalized electrospun nanofibers for tissue engineering and drug delivery, *Adv Drug Delivery Rev*, 61, 1033–1042.

Yu D G, Shen X X, Zhang X F, Zhu L M, Branford W C, *et al.* (2009). Applications of polarization microscope in determining the physical status of API in the wet-spinning drug-loaded fibers, in *Symposium on Photonics and Optoelectronics*, 14–16 August 2009, Wuhan, China. IEEE, New York.

Yu D G, Shen X X, Zheng Y, Ma Z H, Zhu L M, *et al.* (2008). Applications of polarization microscope in determining the physical status of API in the wet-spinning drug-loaded fibers, in *ICBBE. The 2nd International Conference*, *Bioinformatics Biomed Eng*, 1375–1378. IEEE, New York.

© Woodhead Publishing Limited, 2011

Zeng J, Yang L, Liang Q, Zhang X, Guan H, *et al*. (2005). Influence of the drug compatibility with polymer solution on the release kinetics of electrospun fiber formulation, *J Controlled Release*, 105, 43–51.

Zeng J, Xu X, Chen H, Liang Q, Bian X, *et al*. (2003). Biodegradable electrospun fibers for drug delivery, *J Controlled Release*, 92, 227–231.

Zhu X, Chian K S, Chan-Park M B and Lee S T (2005). Effect of argon-plasma treatment on proliferation of human-skin-derived fibroblast on chitosan membrane in vitro, *J Biomed Mater Res Part A*, 73A, 264–274.

Zhu Y B, Gao C Y, Liu X Y and Shen J C (2002). Surface modification of polycaprolactone membrane via aminolysis and biomacromolecule immobilization for promoting cytocompatibility of human endothelial cells, *Biomacromolecules* 3, 1312–1319.

Zong X, Li S, Chen S, Garlick B, Kim K S, *et al*. (2004). Prevention of postsurgery-induced abdominal adhesions by electrospun bioabsorbable nanofibrous poly(lactide-co-glycolide)-based membranes, *Ann Surg*, 910, 240.

© Woodhead Publishing Limited, 2011

8

Medical textiles and thermal comfort

G. SONG, University of Alberta, Canada, W. CAO, California State University, Northridge, USA and R. M. CLOUD, Baylor University, USA

Abstract: Achieving comfort and functionality in hospital apparel is critical for both healthcare workers and patients. The diverse hospital environmental settings and the activities performed by individual personnel pose challenges to the maintenance of thermal comfort and the necessary protective performance of medical apparel. In this chapter, the fundamentals of thermal comfort are introduced. Hospital environments and typical hazards that healthcare workers may be exposed to are discussed. Factors contributing to comfort and protective performance are reviewed with respect to the properties of textile materials and medical apparel. Methods and current standards for evaluating comfort performance are summarized.

Key words: comfort, medical textiles, protective performance, surgical gown.

8.1 Fundamentals of thermal comfort

Human comfort is described as a neutral state and freedom from pain (Hatch, 1993). It is also defined as a 'pleasant state of physiological, psychological and physical harmony between a human being and the environment' (Slater, 1985). When people feel comfortable in their clothing, they feel it both physiologically and psychologically. Psychological comfort depends on a person's preferences; it is a state of ease and the confidence provided by the clothing that is being worn. It often implies the need for specific garments, fabrics, colors and design features with given environmental conditions. Physiological comfort is about the human body's ability to maintain life, and it includes thermal comfort, sensorial comfort and body movement comfort (Hatch, 1993). Thermal comfort is reached when thermal balance between the human body and environment is established, and the proper relationship between the body's heat production and heat loss produces optimum body thermal sensation. It involves the exchange of heat and moisture through the body–clothing–environment system. In ISO 7730 'Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria,' thermal comfort is defined as 'That condition of mind which expresses satisfaction with the thermal environment.' In order for humans to maintain a constant core temperature of 37°C, heat balance must be attained.

The energy conservation equation for heat exchange between body and environment can be simply described as:

© Woodhead Publishing Limited, 2011

$$S = M - W - E - R - C - K \quad [8.1]$$

where S is the heat stored in the body, M is the metabolic heat generated by the human body, W is the total external work performed by the body, E is the evaporative heat flow, R is the radiative heat flow, K is the conductive heat flow, and C is the heat exchange through clothing. In this equation, the radiative heat flow is the exchange of heat between human body and surrounding hot or cold objects, such as furnaces or cold metallic surfaces without direct contact with them. Conductive heat flow is the exchange of heat between a human body and surrounding objects through direct contact. The heat storage rate, S, should be zero ($S = 0$) when the human body is in a state of thermal comfort. If S is positive, the body temperature will rise. The body response at heat accumulation is vasodilation of blood vessels and sweat production. The increasing blood flow allows more heat loss from the skin. If S is negative, heat is dissipated from the body and body temperature will fall. With heat loss, one of the body responses is vasoconstriction of the blood vessels to reduce the blood flow and lower the heat dissipation through the skin. Another body response at heat loss is shivering, which is to generates internal body heat through muscle stimulation.

Metabolic heat, M, is generated in the body cells by a biochemical process and energy consumption in physical activities. It is an important internal adjustable factor of human body thermal balance. The amount of heat generated by metabolism depends on the tasks performed and muscular activity, ranging from 45 W/m^2 while sleeping to 445 W/m^2 during sports activity (Parsons, 1993). Another internal adjustable factor, the evaporative heat flow, E, mainly comes from sweat. Sweating, or the evaporation of perspiration, is an important venue for the human body to regulate its heat balance. Sweat is secreted in liquid form and, when evaporated, forms the evaporative heat flow E to dissipate heat from body. The amount of sweat secretion is a body adjustment response to body temperature. When body temperature rises, sweat secretion increases to allow more evaporative cooling flow. Actually, the dissipation of moisture from body is continuous. It can be insensible perspiration when the body is in a resting state, or sensible perspiration or sweat when the body is engaged in high levels of activity. For cold weather clothing, an important function is to keep the body sweat rate within comfort limits, particularly within the clothing microclimate, and to manage the transfer of moisture from the skin as well as maintain the body in overall heat balance.

The continuous process requires heat exchange between the body and the surrounding environment with clothing often present to mediate the exchange. The heat loss from the body to the environment can be through conduction, convection and radiation. The air gap or micro-climate between the human body and clothing is a critically important factor in determining heat and moisture transfer from the body (Song, 2007).

Fanger (1970) indicates that human thermal comfort is a balance of heat exchange among the body, its clothing and the environment and is affected by six

© Woodhead Publishing Limited, 2011

fundamental parameters: metabolic heat produced by human activity, clothing worn by a human body, and the four environmental variables of air temperature, radiant heat, humidity and air movement. These six parameters determine human heat balance as mentioned in equation [8.1], and therefore influence human response to thermal environments. Fanger posits that three conditions are critical in achieving thermal comfort: the human body must be in heat balance; the sweat rate must be within comfort limits; and the mean skin temperature must also be within comfort limits.

The main role of clothing in thermal comfort is to maintain thermal balance between the human body and its environment. This role is fulfilled by providing thermal insulation or slowing down heat flow from the body to a cold environment. The interaction of clothing with the human body and its environment is complex and dynamic, and it is extremely hard to quantify. The thermal insulation provided by the clothing comprises the clothing materials themselves, the air layers or spaces between the skin and clothing or between layers of clothing; and the existing still (boundary) air layer attached to the outer surface of the clothing. In fabrics or multilayer materials, heat transfer through these materials is mainly by conduction and radiation. The major contribution to thermal insulation provided by the textile material is the dead air trapped in the material structure.

Major properties affecting thermal comfort of clothing include dry thermal resistance, evaporative resistance, air permeability, and moisture management. Heat exchange from clothing can occur by conduction, convection, radiation, evaporation and condensation. These properties are normally measured in a static condition (standing posture using thermal manikin), but in an actual wear situation, body movement and air flow in the environment can reduce the still air layer, thereby reducing thermal resistance, and can create a chimney or pumping effect, thereby increasing loss of heat by convection. As a result, the total insulation of the clothing ensemble changes tremendously.

The main environmental variables that affect human response to the thermal environment are air temperature, mean radiant temperature, humidity, and air movement (wind speed). Changes in these environmental variables affect the thermal balance between the human body and environment as a result of change in heat and mass transfer. The higher the air temperature, the less heat will transfer from the body to the environment. When the environmental temperature is above the skin temperature, the body will gain heat from the environment. The relative humidity in the environment affects moisture transfer from the skin to the environment. Normally, the moisture concentration at the skin is higher than in the environment, so the moisture can transfer from the skin to the environment through evaporation. High moisture concentration or poor evaporative resistance of clothing interferes with moisture transfer and potentially causes discomfort. Increased wind flow promotes heat transfer from body to the environment by convective and evaporative heat transfer. With higher wind speed, the thickness of the still (boundary) air layer can be significantly reduced.

© Woodhead Publishing Limited, 2011

Heat stress can be generated when metabolic heat production cannot be dissipated as described in equation [8.1] and leads to heat storage in the body ($S > 0$). Heat stress is specifically of concern in protective clothing when the clothing system impedes body heat loss. Heat stress can result in heat strain where the body experiences dangerous reactions such as a rise in core temperature, and/or increased heart rate. Profuse sweating may accompany these symptoms but is not able to off-set the heat storage. As heat storage continues, physiological functions become impaired and eventually heat illness, heat stroke or death can result.

In cold environments, cold stress can be developed when negative heat storage from the body ($S < 0$) occurs. In this case, too much body heat is dissipated to the environment and the potential exists for core body and skin temperature to fall. This effect occurs most readily for body parts with large surface area, such as hands, feet, nose, ears and cheeks. The lowering of body temperature can lead to frostbite, hypothermia or even death.

8.2 Healthcare workers and patients in the hospital environment

Clothing takes on usefulness and meaning when donned by the wearer in a given environment. Fourt and Hollies (1970) conceptualized clothing as a system with three elements: person, clothing and environment. Variation of any aspect of the clothing, person and environment triad may affect the interactions among the elements. The concept of the clothing system was applied to the development of a clothing comfort model by Branson and Sweeney (1991). The model indicates that clothing comfort is influenced by physical and psychosocial attributes of the human–clothing–environment triad. An individual forms a comfort judgment based on the interrelationships of these attributes.

Clothing is initially in a static state of existence when it is produced and sold. It becomes dynamic in its interaction with the human body when it is worn in the intended environment. Fourt and Hollies (1970) recognized the role clothing plays in modifying the balance between humans and their environments. Human thermal comfort is a state of mind that expresses satisfaction with the surrounding environment (ASHRAE Standard 55, 1992). A hospital operating room is a special setting with potential for cross-infection between healthcare workers and patients. Clearly protective clothing is needed but should be designed to ensure that health professionals can work comfortably (Mora *et al*., 2001) and efficiently. Appropriate medical clothing used in the operating room plays a mediating role in balancing the protection of healthcare workers with their need for comfort and function in the operating environment (Cao and Cloud, 2010).

To achieve thermal comfort in a hospital setting means that the occupants (surgeons, anesthetists, nurses, technicians and patients) experience physiological, psychological and physical comfort. As with other environments, thermal comfort

© Woodhead Publishing Limited, 2011

in hospital settings is highly related to body metabolism, general level of activity, external temperature, and the insulating/permeable properties of fabric/clothing to moisture, water or air, etc. (Behera and Arora, 2009). When the thermal comfort of healthcare workers is not addressed, their work quality may suffer. Pilcher *et al*. (2002) found that psychophysiological performance dropped by 5.95% when workers were exposed to temperatures > 21°C.

8.2.1 Hospital environment

With the prevalence of human immunodeficiency virus (HIV), hepatitis B and C virus within the healthcare industry, there is an urgent need to keep healthcare workers safe from the occupational hazards of being in contact with bodily fluids. Data from the CDC Surveillance Report (1989) reported more than 2400 healthcare workers suffered occupational exposures to bodily fluids from known HIV-infected individuals, with at least 35 resultant seroconversions. McKinney and Young (1990) established a mathematical model to calculate the surgeon's cumulative risk of acquiring HIV infection in an average 30-year surgical career. Their estimation of the risk of the surgeon acquiring occupationally transmitted HIV infection was 10% in an environment with HIV prevalence in the surgical patient population of 0.1%. In 1996, 49 healthcare workers seroconverted to HIV after occupational exposure, 22 (45%) of whom eventually developed AIDS (CDC report, 1996).

Campbell (1996) pointed out that besides HIV infection, healthcare workers have been infected and killed by hepatitis for decades. Datta *et al*. (2003) found that hepatitis C virus (HCV) is transmitted primarily through large or repeated direct percutaneous exposures to blood among emergency responders. Compared to HCV, hepatitis B virus (HBV) is approximately ten times as transmissible. Both the incidence and prevalence of the HBV infection are substantially higher among hospital-based healthcare workers than among the general population, and infections are consistently associated with the degree of occupational blood exposure. An investigation conducted by Levy *et al*. (1977) presented evidence regarding a sharp increase in HBV cases among the 2000 employees of a general hospital during three years. This data supports the premise that many hospital employees contract hepatitis B from exposure to patients, especially for those who routinely get blood on their skin and clothes at work. Healthcare workers who were infected by HBV and HCV during work in Poland in 2005 were 42.6% out of 314 new cases of occupational diseases (Wilczynska *et al*., 2006).

Lymer *et al*. (1997) suggested that the blood-exposure incidents that actually occur are considerably more numerous than those reported. Pissiotis *et al*. (1997) indicated that healthcare workers often act in a risky way in blood-exposure situations no matter how knowledgeable they are. The surgeon and the first assistant are known to be the primary personnel contaminated with large amounts of blood on the gowns and therefore in the highest risk situation.

© Woodhead Publishing Limited, 2011

Wong *et al*. (1998) found that wearing appropriate protective clothing and being aware of the hazards can significantly change the degree of protection for healthcare personnel. Quebbeman *et al*. (1991) pointed out that gown strike-through was related to the period of time that the gown was worn. Because healthcare workers wear surgical clothing for an average of six to eight hours (Suprun *et al*., 2003), they need protective medical garments that will not leave them feeling either too cold or too warm so as to maintain the high quality of the medical service.

8.2.2 Temperature setting in the operating room

Comfort needs to occur for both the static and active status of clothing. As stated by the Canadian Center for Occupational Health and Safety (CCOHS 2010), the ambient temperature could be the most critical factor for maintaining thermal comfort indoors when air movement is virtually absent and relative humidity can be kept at about 50%. The recommended general guidelines for the temperature in an operating room should be in the range of 68–76°F (20–24°C), relative humidity (RH) should be in the range of 50–60% (ASHRAE, 2005).

Previous research established the existence of thermal zones in the operating room and reported thermal differences between zones and people in the operating room. Woods *et al*. (1986) divided the operating room into three zones. Zone 1 was labeled 'microenvironment', in which surgeons were working with patients under a surgical light. Zone 2 was labeled the 'sterile zone' to include the area with the surgical instruments and equipment right outside zone 1. Assistant nurses circulate through zones 1 and 2. Zone 3 was labeled as the 'mini-environment'. It was the least clean area because it includes nurses, technicians and anesthetists. Due to the higher air speeds and lower turbulence intensity expected in zone 1 and 2, more convective heat loss is required for surgeons and nurses. The air temperatures among zones 1, 2 and 3 varied by as much as 34.7°F (1.5°C). Mora *et al*. (2001) indicated that air temperature, radiant temperature, and the operative temperature (taking into account the effect of airflow) were almost the same in zones 2 and 3. In zone 1, the mean radiant temperature is 37.4°F (almost 3°C) higher than the operative temperature due to the thermal radiation from the surgical lights. The operative temperature in zone 1 differed from the rest of the room about 41.7°F (5.4°C). In addition to indoor environmental factors (air temperature, radiant temperature, air speed and humidity) specified by ASHRAE (2005), personal factors (metabolic rate and clothing insulation) contribute greatly to the healthcare workers' thermal comfort.

Temperature preferences can vary among healthcare workers and patients due to their different activities in the operating room. Most surgeons conduct operations while standing, sometimes bending, but in a dynamic work mode; anesthesiologists perform in a more stationary position (Sudoł-Szopińska and Tarnowski, 2007). There is not one temperature that can satisfy all persons who work in the operating room.

© Woodhead Publishing Limited, 2011

Wyon *et al*. (1968) reported the highest comfort index temperature for surgeons was 64°F (18°C), for the staff was 68.9°F (20.5°C). (Index temperature combines the actual air temperature and the mean radiate temperature under 50% RH and at mean air velocity of 0.127 m/s.) Olesen and Bovenzi (1985) recommended equivalent temperatures (operative temperature plus the effect of airflow) for anesthetists were 73°F to 76°F (23°C to 24.5°C), for nurses were between 72°F and 76°F (22°C to 24.5°C), and for the surgeons about 66°F (19°C). Optimum steady state conditions for patients were air temperature between 70.7°F and 71.6°F (21.5°C and 22°C) and a relative humidity between 30% and 70%, with air velocity less than 0.1 m/s and mean radiant temperature close to air temperature (Smith and Rae, 1975). Mora *et al*. (2001) pointed out that the operative temperature felt by surgeons was about 25.6°F to 37.4°F (2°C to 3°C) higher than all the other staff. Therefore, it is impossible to offer an acceptable thermal comfort environment for all. Some workers may have to adjust their dress to suit the conditions necessary for surgeons, or adjustments may be needed in surgeons clothing to address this issue. Therefore to provide surgeons with the best conditions for them to work comfortably without compromising other people's needs is the optimum solution (Mora *et al*., 2001).

8.2.3 Healthcare workers and patients

Healthcare workers can maintain their thermal comfort by balancing the heat generated by metabolism and body movement with the heat dissipated by dressing appropriately. Any minor deviation from comfort may be stressful and affect their quality of work and safety. Surgeons and nurses metabolic rates vary with their duties. Surgeons take the major responsibilities in performing the operation successfully. In the operating room, there is less chance for the surgeons or nurses to reduce their activity level to release the heat or prevent its generation. Konarska *et al*. (2007) pointed out that body movements and postures of volunteers while performing work tasks impacts the heat exchange between human bodies and the operating room as well.

Wyon *et al*. (1968) found that the radiation from operating room lamps was a factor that influenced ambient temperature. Surgeons were exposed to the radiation temperature from both the light beam and the hot lamp casing. Surgeons' elevated skin temperatures showed clearly the heating effect from the radiation of the surgical lights (Mora *et al*., 2001). Surgical assistants, scrub nurses and anesthetists were exposed to radiation from the operating room lamp as well, but the radiation had less effect on their thermal comfort because they were farther from the lamps than the surgeons (Wyon *et al*., 1968). The effect is heightened by the higher activity level of surgeons (zone 1) as compared to surgical staff in zones 2 and 3.

Wyon *et al*. (1968) observed that 50% of surgeons were visibly sweating at an ambient temperature of 65°F (18.3°C), while 50% of anesthesiologists were sweating at 77°F (25°C), 50% of all the other staff were sweating at 82°F (27.8°C).

© Woodhead Publishing Limited, 2011

Surgeons, nurses and anesthesiologists work under different stress levels. The varied stress levels lead to their different sensations of heat (Mora *et al*., 2001). Mazzacane *et al*. (2006) found that 'first' nurses were comfortable 75% of the time, while the 'first' surgeons felt comfortable only 25% of the time, and the second surgeon felt comfortable 67% of the time. The researchers attributed these differences in comfort evaluation to the healthcare workers' different reactions to the scialytic lamp and their responsibility for the outcome of the surgery.

Thermal comfort changes with the type of surgery due to different levels and types of activities required for the staff, different types and numbers of equipment and lights needed, different numbers and function of patients presented (Melhado *et al*., 2006). Considering the complexity of interactions between potential operating room conditions (temperature, heat sources) and differences in staff and their activity levels, researchers agree that variation in protective medical clothing is the best way to resolve thermal comfort issues (Wyon *et al*., 1968; Melhado *et al*., 2006). Contributions of medical clothing to improved thermal comfort can have a significant positive influence on the work performance of medical personnel, particularly where that clothing would be worn for not less than six hours a day (Suprun *et al*., 2003).

8.3 Thermal comfort of medical textiles: surgical gowns

Medical textiles include non-implantable (wound dressing, bandages, plasters, etc.), implantable (sutures, vascular grafts, artificial ligaments, artificial joints, etc.), extracorporeal devices (artificial kidney, liver and lung) and healthcare and hygiene products (bedding, clothing, surgical gowns, cloths, wipes, etc.) (Horrocks and Anand, 2000; Rajendran and Anand, 2003). In the operating room, healthcare workers wear different clothing based on their job responsibilities. The AORN handbook (2003) *Recommended Practices*, describing selection of medical clothing, indicates that surgical gowns play a critical role in modifying the medical personnel's response to temperatures in the operating room and should assist in maintaining an isothermal environment for healthcare workers. Surgeons usually perform a demanding job under stress, therefore improving their thermal comfort should take precedence over all the other healthcare workers' during the operation (Wyon *et al*., 1968). Nurses and anesthetists can increase their clothing insulation to remain consistent with surgeons needs (Mora *et al*., 2001). It is also essential to discuss the comfort of surgical gowns, because it has been shown that thermal comfort is highly correlated with the accuracy and safety of the operation (Behera and Arora, 2009). The thermal comfort of the clothing is directly influenced by the type of the materials used and the properties of those materials, including thermal conductivity, water vapor permeability, air permeability and water impermeability (Behera and Arora, 2009). For example, surgeons and assistants must wear non-transpiring paper overalls beneath plasticized overalls in some surgeries like

© Woodhead Publishing Limited, 2011

orthopedics and neurosurgery, and may wear lead overalls and/or lead thyroid collars if X-rays are needed in other surgeries. A study of the second surgeon in this type of surgical apparel indicates significant increases in skin temperature from 89.6°F to 93.2°F (32°C to 34°C) during the surgery (Mazzacane *et al*., 2006).

8.3.1 Heat and moisture transfer

As we know, heat is transferred from body through dry forms (conduction, convection and radiation) and wet forms (evaporation of skin moisture). These forms of heat transfer apply in the operating room as well. Conductive heat loss occurs when heathcare workers touch any object in the operating room which is cooler than their skin temperature. For example, when they touch metal instruments, equipment, bedding, patients, or operating tables/beds, heat will pass from the healthcare worker to the object. Convective heat loss occurs when healthcare workers encounter air movement from the air handling system or create air movement by moving their bodies during the operation. In addition to air movement removing heat from the outer surface of the surgical apparel, air entering at the gown hem will rise and may carry away heat if the garment is vented in such a way as to allow exit of the heated air (aka, chimney effect). Healthcare workers contribute to the thermal environment by radiant heat loss from their bodies, but also gain the heat from the radiation of the lights and all the other objects in the operating room.

Evaporative heat loss is an effective thermal balancing mechanism that is utilized naturally by our bodies through sweating. However, all of these mechanisms of heat loss are affected by the clothing worn. Some heat could be evaporated from healthcare workers through the interstices of the gown fabrics, the interfaces between body and gown fabrics, and the exposed skin. The bodies of surgical workers are covered by surgical clothing; therefore the heat resistance of the clothing materials is important in determining thermal comfort.

Thermal resistance of surgical gowns is influenced by material properties (fibers, yarns, fabrics, finishes) and the effects of garment structure and layering. A critical aspect in the thermal resistance of any clothing system is the degree to which air is trapped in the system. Air conducts heat more slowly than fibers (Fourt and Hollies, 1970); therefore, gown fabrics or layers which trap less air allow more heat loss from the body than fabrics or layers with more enclosed air. Thermal resistance of the gown material also depends on moisture regain of the fibers since water is a good conductor of heat (Behera and Arora, 2009). Fibers with higher moisture regain can encourage more heat loss.

8.3.2 Breathability and air permeability

Insensible heat is lost from the body through water vapor. If the breathability of a fabric allows moisture to migrate away from the body, the fabric is said to have

© Woodhead Publishing Limited, 2011

high moisture vapor transmission rate. Otherwise the blocked moisture vapor condenses on the skin in the form of sweat, which may cause discomfort due to a clammy or sticky feeling. Wong *et al*. (2004) concluded that surgical gowns with low air permeability would not allow movement of air and moisture away from the body easily therefore the wearer would feel thermal discomfort and endure heat stress. One of the unfavorable properties which inhibit the healthcare workers using protective medical clothing is low air permeability (Suprun *et al*., 2003). Lee and Obendorf (2006) indicated that air permeability of electrospun polypropylene webs decreased with increasing web thickness.

The air permeability of fabric is associated with convective heat flow, whereas the moisture vapor transmission rate is associated with diffusion. Nevertheless, many woven and nonwoven fabrics with higher air permeability allow increased transfer of moisture vapor and heat flow. Ideal fabrics should have high air permeability and increased moisture vapor transmission rate without compromising the liquid barrier performance.

8.3.3 Textile materials used for medical textiles and factors contributing to thermal comfort

Fibers/yarns/fabrics and their relationship with thermal comfort

Natural fibers used in healthcare textiles include cotton, silk and regenerated cellulosic fibers (viscose rayon) (Fisher, 2006). More recently the use of synthetic fibers, such as polyester, polyamide, polytetrafluoroethylene (PTFE) and polypropylene, have led to advancements and innovations in the protective and comfort aspects of medical and surgical textiles (Rigby *et al*., 1994).

Specifically, the following parameters in terms of the fiber type will affect the dry thermal resistance: staple fiber versus filament, round cross section versus triangular one, fine fiber versus a coarse one, crimped fiber versus a straight one, crystallized fiber versus an amorphous one. Yarn structures, such as textured yarn versus regular one, ply yarn versus single yarn, high twist yarn versus low twist one, are also factors to be considered. Aibibu *et al*. (2003) point out that pore sizes, geometry and numbers of pores in a fabric depend on the yarn and fabric structure, and round cross sections of the filaments can provide higher density while triangular cross sections and coarse filaments result in wider pore spaces; weaving type, fabric count, filament counts and yarn spacing are all important parameters affecting pore sizes. Larger pore sizes increase moisture vapor transmission, leading to improved thermal comfort of the materials. Other factors in fabric structure also contribute to the thermal comfort of gown materials. For example, thicker fabric versus thin fabric, heavier fabric versus lighter fabric, high fabric count versus low fabric count, laundry method and times, finishing techniques which impact the fabric structure are all factors impacting to the porosity and air permeability of fabrics and its subsequent water vapor

© Woodhead Publishing Limited, 2011

transmission. Hatch *et al*. (1990) investigated the perceived comfort response to fabric and indicated that thermo-physiological comfort parameters related more to fabric structures than to fiber content.

Fabrics used in surgical gowns and thermal comfort

Surgical gowns may be constructed of either single-use or reusable materials. Each of these has advantages and disadvantages, which depends on the fabric construction and performance characteristics of materials (Rutala and Weber, 2001). Woven reusable surgical gowns have traditionally been made of cotton muslin and tight weaves treated with fluid-repellent compounds. Now most gowns are made of polyester or polyester blended with cotton (Laufman *et al*., 2000). All-cotton muslin is a loosely woven, 140-thread-count per inch, soft and absorbent fabric (Rutala and Weber, 2001). Once a popular fabric for medical textiles, this fabric was breathable with high air permeability, but has moved out of the market due to its low liquid-penetration resistance. The later-used polyester and cotton blended fabric was good in thermal comfort but was also challenged in liquid penetration protection even in 180-thread-count. Abreu *et al*. (2003) found that cotton and traditional cotton–polyester textiles meet the requirement of comfort, but not the demand for resisting microbial penetration. T280 barrier polyester sheeting, which is a woven fabric with a water-repellent chemical finish can be used to provide increased protection against strike-through liquids and microorganisms, but the thermal comfort could be a problem.

Comparatively tightly woven filament polyester fabrics may cause more discomfort to healthcare workers than tightly woven cotton muslin due to differences in hydrophobic/hydrophilic properties of fibers, lofty/stiffness of yarn/fabrics and density of fabrics. In addition, laundry and finish can also influence the thermal comfort of reusable gown materials. Leonas (1998) found that the porosity of tested woven fabrics increased after laundry, and she proposed the more open structure would improve the comfort level of the gowns. Cho *et al*. (1997) found that dual-functionally-finished surgical gowns (made by cotton muslin and nonwoven) allowed more heat to be dissipated from the skin of subjects than untreated gowns as measured by lower microclimate temperature and humidity.

Single-use materials are usually made from nonwoven fabric, which is defined as a manufactured sheet, web or batt of directionally or randomly oriented fibers or filaments, excluding paper and paper products, that are woven, knotted, tufted or stitch bonded and have not been converted onto yarns. Nonwovens fibers are bonded to each other by friction and/or cohesion and/or adhesion (AORN, 2003). According to Rutala and Weber (2001) of surgical gown material, the three most commonly used nonwoven fabrics for surgical gowns and drapes are spunlace, spunbond–meltblown–spunbond (SMS) and wet-laid. Spunlace nonwoven fabric is a hydro-entangled material, usually made from wood pulp

© Woodhead Publishing Limited, 2011

and polyester fiber. SMS fabric refers to a fabric consisting of three thermally or adhesively bonded layers (spunbond layer provides the strength, meltblown layer is the barrier). Wet-laid fabric is made by suspending wood pulp or a blend of polyester and wood-pulp fibers in water to obtain a uniform dispersion, and then separating the fibers from the slurry by draining the water through a fine mesh screen.

In a study by Stanley (1994), nonwoven gown fabrics were evaluated cooler than reusable ones because of their lighter weight. Fisher (2006) found that nonwoven fabrics with SMS structure were claimed to have the same level of comfort as garments made from microfiber. However, the comfort levels of conventional nonwoven fabrics have been challenged due to low air permeability and moisture vapor transmission rate (Lee and Obendorf, 2007a,b).

Additional materials in the form of coatings, reinforcements, laminates or plastic-film are often added to reusable and single-use products to improve their performance in barrier resistance, absorbency and non-slippage. Rutala and Weber (2001) provide the following categorization of reinforcement approaches: reinforced fabric (second layer of fabric used to reinforce base materials); impervious fabric with liquid-repellent finish; layered fabrics with a highly resistant membrane between two layers; and fabric reinforced with liquid-proof protection membrane. Those approaches improve the protective performance of gown materials, but whether they take into consideration the thermal comfort of the wearers is questionable. Membranes and coatings tend to impair wearing comfort (Aibibu *et al*., 2003). Pissiotis *et al*. (1997) evaluated the comfort level of four types of nonwoven gowns with and without reinforcement. Surgeons felt less comfortable when wearing the reinforced gowns due to less heat transfer and more sweating in areas where the gown was covered by another layer of fabric or a plastic.

New technology used in surgical gowns and thermal comfort

With the concern for improving comfort of gown materials without sacrificing protective performance, new approaches such as electrospun technology were studied for their application in protective clothing which has to provide liquid protection. Lee and Obendorf (2007a,b) compared the air permeability and moisture vapor transmission rate among various layered fabric systems including microporous materials, nonwovens and electrospun nanofiber webs. They found that conventional microporous and laminated fabrics both have very low air permeability, but microporous materials have a better moisture vapor transmission rate than nonwovens. Electrospun nanofiber webs present a middle level of comfort between microporous materials and nonwoven fabrics. Another study by Lee and Obendorf (2007a,b) focused on whether a change in density of electrospun nanofiber webs would be a contributing factor for thermal comfort. The researchers electrospun polyurethane nanofibers as an interconnected membrane-like structure which could

© Woodhead Publishing Limited, 2011

cover the macropores of nonwoven fabric and create smaller pores in a layered system. The thin layer significantly changed the air permeability of the material, the air permeability of the higher density layer dropped due to the change in thickness (Lee and Obendorf, 2006), but was still higher than most of the current reinforced materials. The conclusion of the authors was that different combinations of electrospun nanofiber layers could create more protective and more comfortable materials due to the change in pore size.

Researchers continue studies to increase the protective performance of surgical gowns without sacrificing the comfort. One approach is improving the low water vapor permeability of the solid polymer-membrane fabric by coating it with a microporous polymer (either PTFE (Teflon)-based or polyurethane-based) to provide smaller surface pores than the inter-yarn spaces of a woven fabric (Behera and Arora, 2009). This coating is purported to ensure that even the smallest water droplet will be repelled, yet air and water vapor can still easily pass through and provide comfort for the wearer (Behera and Arora, 2009).

Another polymer-based surface treatment, a monolithic coating that does not contain any microscopic holes, was applied in surgical gowns to improve the thermal comfort as well. In this fabric, the transport of water vapor is done through the process of molecular diffusion, where the membrane absorbs wetness on one side and releases it on the other side (Behera and Arora, 2009). Both microporous and monolithic coatings create higher breathability than multi-layer fabrics (Behera and Arora, 2009). Elements from both the microporous and monolithic technologies are combined in bicomponent barriers, where they can be layered one on top of the other to maximize the comfort of gown materials (Behera and Arora, 2009).

Another innovative approach to comfort in medical textiles, Smart Gowns®, employs a microfiber composite in a monolithic film which reacts to increasing temperature by allowing increased moisture transfer rate from the body. The moisture vapor transfer rate of the material can increase exponentially as the moisture level rises beneath the garment (Behera and Arora, 2009). Acturel® brand is one such fabric which claims to be a breathable, impervious barrier material that adjusts to body temperature over time. Acturel® fabric is made of three layers: polyester nonwoven as an inner layer, Hytrel® as a breathable membrane sandwich or middle layer, and spunbonded polypropylene as the outer layer (Anonymous, 2010). Another study showed that a complex of ultra-thin polyester and polyamide fibers will accommodate the water-repellent and moisture transference needs (Suprun *et al*., 2003).

8.3.4 Clothing system (surgical gowns) and its characteristics for thermal comfort

In addition to the material itself, garment size, fit, structure and layers affect heat retention/storage. May-Plumlee and Pittman (2002) found that reusable gowns fit

© Woodhead Publishing Limited, 2011

better than disposable surgical gowns due to the ease in adjusting necklines and fit to the torso. Their survey investigating wearers' and purchasers' satisfaction with surgical gowns reported that surgeons and nurses did not feel comfortable in the gowns due to the size (too large). This size issue was also associated with safety concerns for exposure to patients' blood and body fluids. Brandt (1993) also concluded from survey data that changes in gown fit and sizing could influence comfort.

Ellis (2005) discusses the impact of structural design features such as neckline, sleeves, and cuffs on overall fit and subsequently on the comfort of the surgical gowns. Adjustable fit can be achieved through the use of closure features such as snaps, hook and loop or ties in neckline or waist and rib knit cuffs. May-Plumlee and Pittman (2002) point out that sleeve design, whether raglan style or set-in sleeves, and variations in sleeve length and width can contribute to bulk and excess fabric in the shoulder and upper chest area, which would impact the heat transfer. (The air gap between the garment and the surgeon's body depends on the size and fit of the garment. Increasing or decreasing this gap will influence convective heat transfer between surgeon's body and external environment since air is a good thermal insulator.) Konarska *et al*. (2007) performed a study to compare thermal insulation of three medical clothing systems using thermal manikins and volunteers. They found that clothing fit influences heat insulation due to the boundary air layer in-between the body and the clothing or between clothing layers.

Kimberly-Clark has designed gowns with back panels angled upward from each side to improve heat release through ventilation (May-Plumlee and Pittman, 2002). Malik *et al*. (2006) assessed the comfort of three surgical clothing systems used during joint arthroplasty and found that the temperature within disposable gowns went up with the duration of the operation while the temperature within the Charnley system was decided by the outside temperature.

Much of the research related to thermal comfort in medical clothing has addressed objective factors; however, subjective influences will also be reflected in thermal comfort assessments of wearers. Wyon *et al*. (1968) acknowledged that discomfort assessments are affected by both physical and mental state. Under the expectation for performing accurately and wisely, surgeons endure high mental stress in the operating room, which can also lead to increased heat generation in the body. Sudoł-Szopińska and Tarnowski (2007) explained that healthcare worker's stress could be increased during operations of patients with multiple injuries and those involving transplants, deaths, teamwork, or work overload. In these cases, psychological discomfort adds to the thermal burden and thus to the physical aspects of thermal comfort. Wyon *et al*. (1968) indicated that the 'atmosphere' (tense or relaxed) in the operating room, the degree of movement/exits and the noise level in the operating room were other subjective factors affecting thermal comfort of healthcare workers.

© Woodhead Publishing Limited, 2011

8.4 Evaluation and testing of thermal properties for medical textiles

The key in achieving thermal comfort is to obtain heat and moisture balance between a human body and its surrounding environment. Clothing as our near environment serves as both a barrier and transporter of heat and moisture. The physical phenomena of heat and moisture transfer are dependent on the physiological state of the human body, the properties of the textiles and clothing worn and the environmental conditions. These three factors may be studied separately for their effects, but holistic studies of thermal comfort are also important.

Clothing comfort can be evaluated or predicted by objective and subjective methods (Umbach, 1983). These methods include different levels of testing and evaluation, from assessing physical properties of textile material to determining clothing thermal properties using sweating manikins, or human trials. Objective methods are mainly focused on characterizing the heat moisture transfer (or liquid transfer) property of textile materials or clothing.

8.4.1 Fundamental textile properties

Several methods or standards have been developed to measure thermal resistance and moisture vapor resistance. ASTM C 518 'Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus', ASTM D 1518 'Standard Test Method for Thermal Transmittance of Textile Materials', and ASTM F 1868 'Standard Test Method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate' are developed to measure thermal resistance or insulation of fabrics or composite, but with different environmental considerations. ASTM C 518 is designed to measure material thermal insulation only with no consideration of boundary air layer resistance (similar methods are in ISO 5085-1 and ISO 5085-2), but in ASTM D 1518 and ASTM F 1868, the boundary air layer resistance is considered; one is still air conditions and one is moving air conditions (with simulation of 1 m/s wind speed). Previous studies demonstrate (Ding *et al*. 2010a,b) that total thermal resistance decreases with increases in wind speed. A relatively large increase occurs in the range of 0–5 m/s. For cold weather protective clothing, the effect of wind speed on clothing thermal insulation and thermal comfort is called the wind chill effect. In surgical suites, normally the thermal environment is unbalanced. Surgical theatres are maintained at positive pressure, formed by a sterile curtain created by a downward flow of air (Ho *et al*., 2009). The primary purposes for ventilation and air flow patterns in surgical theatres are the thermal comfort and contaminant removal effectiveness (Mora *et al*., 2001).

Cup methods are used to measure the water vapor transmission through fabrics (ASTM E 96 and ASTM E 96 Procedure BW). The cup can be inverted with waterproof materials and no air layer involved. The water vapor resistance of the air

© Woodhead Publishing Limited, 2011

layer existing in the cup method may be higher than fabric itself. The method of sweating guarded hot plate (ISO 11092) is based on a skin model. The model consists of a hotplate (skin), fabric (sample) and controlled environmental conditions (wind, temperature, relative humidity). The evaporative resistance of fabric/composite is determined by measuring the power supply to the plate to maintain the skin temperature at 35°C. Steady-state and transient water vapor permeation behavior of fabrics can be measured by dynamic moisture permeation cell (DMPC) as described in ASTM F2298. This method was developed to test the moisture vapor transport properties of fabrics, membranes, and laminates. Two options are provided within the test methods: a diffusion test and a combined convection/diffusion test. The sweating hotplate method was compared to the DMPC and a good correlation was found (Gibson *et al*., 1997). Additionally the sweating guarded hot plate method also exhibits a correlation to cup methods, but not for hydrophilic materials (Gibson, 1993). Different methods to measure water vapor permeability were compared and correlation with the sweating guarded hot plate method as described in ISO 11092 (McCullough *et al*., 2003).

Liquid transport in textile materials is another important feature for thermal comfort. The wicking ability of fabric can be tested with a vertical strip method and drop test. Another test system is the Gravimetric Absorbency Testing System or GATS. The system incorporates a special test cell to assess the absorption and evaporation behavior of fabrics. The test data provides absorption capacities and rates, and percentage of moisture evaporated by the fabric (Barker, 2002).

8.4.2 Thermal manikins

Thermal manikins have been used in comfort studies for many years. The major advantage of the manikin test is realistic simulation of heat and moisture transfer interactions between body, clothing and the surroundings. Using manikins, clothing thermal insulation and evaporative resistance can be measured. The effects of garment size (air layers), fit and components on overall garment comfort can be assessed. The most significant contribution of the manikin evaluation system is its application in developing models to predict comfort and thermal stress associated with particular environmental conditions and varying levels of human body metabolic heat production. It should be noted that the manikin tests only measure thermal properties of clothing and do not reflect any physiological effects. Recent developments in moving manikins have provided more realistic measurement of clothing thermal insulation and evaporative resistance for the body in motion. The body movement creates a pumping effect which promotes convective heat loss and decreases the insulation value of clothing (Havenith and Nilsson, 2004, Bouskill *et al*., 2002).

8.4.3 Human trial

Human trial methods are also used in comfort evaluation for functional and protective clothing, such as surgical gowns, chemical protective clothing, fire

© Woodhead Publishing Limited, 2011

fighter clothing system or active sportswear. Such methods are used to evaluate the physiological impact of the specific clothing on human body. Wear trials collect human responses to test clothing or textile materials while the participants conduct a series of simulated activities. For controlled conditions, a walk-in chamber is used to create the desired temperature and relative humidity in the environment. The protocol includes periods of physical activity alternating with periods of rest in different climatic conditions. An important part of the activity routine is the exercise period designed to promote sweating. Both objective and subjective assessment parameters can be collected during human trials. The objective assessments include body core temperature, heat rate, skin temperature, body mass loss, and relative humidity in the microclimate (air gap between human body and clothing). Several developed methods can be followed to measure these parameters. For instance, the ISO 9886 (2004) 'Ergonomics – Evaluation of thermal strain by physiological measurements' introduced several methods that can be used to monitor the body core temperature. Subjective assessments can be obtained using a customized questionnaire to rate the thermal comfort feeling or responses before, during and after the trial. This assessment is described in ISO 10551 (1995). Descriptor terms are defined to be representative of the fabric properties that are most relevant for the clothing application. A proper selection of environmental conditions, protocol design, human subject selection and preparation are crucial in human trials.

8.5 Future trends

The key in achieving high performance in surgical gowns is to provide good barrier and comfort. The research related to thermal comfort in the operating room is complex due to the uniqueness of the environment and the different expectation among the surgeons, nurses and anesthesiologists (Wyon *et al*., 1968). The evaluation of the thermal comfort of healthcare workers during different surgeries is greatly needed (Melhado *et al*., 2006). The use of an emerging technology, phase change microcapsules embedded in the surgical gowns, has been suggested (Mondal, 2008). Phase change materials interact with the microclimate around the human body, responding to the change of surgeon's skin temperature due to the physical activity, mental stress and any variations in the operating room. Several new products of surgical gowns have been reported in Behera and Arora (2009) including the Smart gowns discussed previously. Further work in this area is merited. Layering techniques will likely continue allowing for development of layers with targeted functions rather than a single layer that performs all of the comfort functions. More work is needed to consider the variable needs of surgical staff in various comfort zones and the effects of garment design on it. Lee and Obedorf (2006) have suggested that, using electrospun technology, different thicknesses of nonwoven web/laminate could be sprayed directly onto three-dimensional garments as needed to improve their properties

© Woodhead Publishing Limited, 2011

without restricting the shape of garments. Other solutions suggested include the use of reflective clothing to cover a surgeon's head and upper body due to the thermal radiation from surgical lights, and moistened clothing for evaporative cooling (Mora *et al*., 2001). It is clear that the need for improvements in thermal comfort of medical clothing are still needed, although much excellent work has been done.

8.6 Sources of further information and advice

Song G (Ed.) (2010). *Improving Comfort in Clothing*. Woodhead Publishing, Cambridge, UK, ISBN 1 84569 539 9.

Van Langenhove L (Ed.) (2007). *Smart Textiles for Medicine and Healthcare*: *Materials, Systems and Applications*. Woodhead Publishing, Cambridge, UK, ISBN-13: 978-1-84569-027-4.

8.7 References

Abreu M J, Silva M E, Schacher L and Adolphe D (2003). Designing surgical clothing and drapes according to the new technical standards. *Int J Clothing Sci Technol*, 15(1), 69–74.

Aibibu D, Lehmann B and Offermann P (2003). Image analysis for testing and evaluation of the barrier effect of surgical gowns. *J Textile Apparel Technol Manage*, 3(2), 1–7.

Anonymous. DuPont. The miracles of science™. Available: http://www2.dupont.com/DuPont_Home/en_US/index.html. [Accessed 18 January 2010].

Anonymous (2003). Recommended practice for selection and use of surgical gowns and drapes. *AORN*, 1, 206–210.

ASHRAE (2003). ASHRAE Handbook: *Applications*. American Society of Heating, Refrigerating and Air-conditioning Engineers. Inc., Atlanta, GA.

ASHRAE (2005). ASHRAE Handbook: *Fundamentals*, *Thermal Comfort*. American Society of Heating, Refrigerating and Air-conditioning Engineers Inc, Atlanta, GA.

Barker R L (2002). From fabric hand to thermal comfort: the evolving role of objective measurement in explaining human comfort response to textiles. *Int J Clothing Sci Technol*, 4, 181–200.

Behera B K and Arora H (2009). Surgical gowns: A critical review. *J Ind Textile*, 38(3), 205–231.

Bouskill L M, Havenith G, Kuklane K, Parsons K C, Withey W R (2002). Relationship between clothing ventilation and thermal insulation. *AIHAJ*, 63(3), 262–268.

Brandt B (1993). Surgical gowns: a survey of wearer and purchaser satisfaction with protection. Nonwovens Industry, 1 September. Available: http://www.thefreelibrary.com/Surgical+gowns:+a+survey+of+wearer+and+purchaser+satisfaction+with+...-a014428963

Branson D H and Sweeney M M (1991). Conceptualization and measurement of clothing comfort: Toward a metatheory. In *Critical Linkages in Textiles and Clothing: Theory, Methods and Practice*, Kaiser S and Damhorst M L (eds.). ITAA Publishers, Monument, CO. pp. 94–105.

Campbell S L (1996). Creative approaches to PPE development. *OH and S Canada*, 12, 82–90.

© Woodhead Publishing Limited, 2011

Canadian Center for Occupational Health and Safety (CCOHS) (2010). Available: http://www.ccohs.ca/oshanswers/phys_agents/thermal_comfort.html

Cao W and Cloud R (2010). Improving comfort in clothing, in *Improving Comfort in Medical Textile Applications*. Woodhead Publishing Ltd, Cambridge, UK, Chap 17.

Cho J, Tanabe S and Cho G (1997). Thermal comfort properties of cotton and nonwoven surgical gowns with dual functional finish. *J Physiol Anthropol*, 16(3), 87–95.

Datta S D, Armstrong G L, Roome A J and Alter M J (2003). Blood exposures and hepatitis C virus infections among emergency responders. *Arch Intern Med*, 163, 2605–2610.

Ding D, Tang T, Song G and McDonald A (2010a). Characterizing the performance of a single-layer fabric system through a heat and mass transfer model. Part 1: Heat and mass transfer model. *Textile Res J*, 0040517510388547, first published on 22 November 2010.

Ding D, Tang T, Song G and McDonald A (2010b). Characterizing the performance of a single-layer fabric system through a heat and mass transfer model. Part 2: Thermal and evaporative resistances. *Textile Res J*, 0040517510395994, first published on 1 March 2011.

Ellis K (2005). Evaluating and purchasing surgical apparel and sharps. Available: http://www.infectioncontroltoday.com

Fanger P O (1970). *Thermal Comfort*, Danish Technical Press, Copenhagen.

Fisher G (2006). Development trends in medical textiles. *J Asia Textile Apparel*, Available: http://www.adsaleata.com/Publicity/ePub/lang-eng/article-40/asid-76/Article.aspx

Fourt L E and Hollies N R S (1970). *Clothing and Comfort*. Marcel Dekker Inc., New York.

Gibson P W (1993). Factors influencing steady-state heat and water-vapor transfer measurements for clothing materials, *Textile Res J*, 63, 749–764.

Gibson P W, Kendrick C E, Rivin D and Charmchi M (1997). An automated dynamic water vapor permeation test method. In *Performance of Protective Clothing*, 6th volume, Stull J O and Schwope A D (eds.). ASTM STP 1273, ASTM, West Conshohocken, PA, pp. 93–107.

Hatch K L (1993). *Textile Science*, West Publishing Company, New York.

Hatch K L, *et al*. (1990). In vivo cutaneous and perceived comfort response to fabric. 1. Thermophysiological comfort determinations for 3 experimental knit fabrics. *Textile Res J*, 60(7), 405–412.

Havenith G and Nilsson H O (2004). Correction of clothing insulation for movement and wind effects, a meta-analysis. *Eur J Appl Physiol*, 92(6), 636–640.

Ho S H, Rosario L and Rahman M M (2009). Three-dimensional analysis for hospital operating room thermal comfort and contaminant removal. *Appl Therm Eng*, 29(10), 2080–2092.

Horrocks A R and Anand S C (2000). *Handbook of Technical Textiles*. Woodhead Publishing Ltd, Cambridge, UK.

Konarska M, Soltynski K, Sudol-Szopinska I and Chojnacks A (2007). Comparative evaluation of clothing thermal insulation measured on a thermal manikin and on volunteers. *Fibers Textile East Eur*, 15(2), 73–79.

Laufman H, Belkin N L and Meyer K K (2000). A critical review of a century's progress in surgical apparel: How far have we come? *J Am Coll Surg*, 191, 554–568.

Lee S and Obendorf S K (2006). Developing protective textile materials as barriers to liquid penetration using melt-electrospinning. *J Appl Polymer Sci*, 102(4), 3430–3437.

Lee S and Obendorf, S K (2007a). Transport properties of layered fabric systems based on electrospun nanofibers. *Fiber Polym*, 8(5), 501–506.

© Woodhead Publishing Limited, 2011

Lee S and Obendorf S K (2007b). Use of electrospun nanofiber web for protective textile materials as barriers to liquid penetration. *Textile Res J*, 77(9), 696–702.

Leonas K K (1998). Effect of laundering on the barrier properties of reusable surgical gown fabrics. *Am J Infect Control*, 26, 495–501.

Levy B S, Harris J C, Smith J L, Washburn J W, Mature J, *et al*. (1977). Hepatitis B in ward and clinical laboratory employees of a general hospital. *Am J Epidemiol*, 106, 330–335.

Lymer U, Schutz A and Isaksson B (1997). A descriptive study of blood exposure incidents among healthcare workers in a university hospital in Sweden. *J Hosp Infect*, 35, 223–235.

Malik M, Handford E, Staniford E, Gambhir A and Kay P (2006). Comfort assessment of personal protection systems during total joint arthroplasty, using a novel multi-dimensional evaluation tool. *Ann R Coll Surg Engl*, 88, 465–469.

May-Plumlee T and Pittman A (2002). Surgical gown requirements capture: A design analysis case study. *J Textile Apparel Technol Manage*, 2(2), 1–10.

Mazzacane S, Giaconia C, Costanzo S, *et al*. (2006). On the assessment of the environmental comfort in operating theatres. Available: http://www.aiha.org/aihce06/handouts/c2mazzacane1.pdf

McCullough E A, Kwon M and Shim H (2003). A comparison of standard methods for measuring water vapour permeability of fabrics. *Measure Sci Technol*, 14(8), 1402–1408.

McKinney W P, Young M J (1990). The cumulative probability of occupationally-acquired HIV infection: The risk of repeated exposures during a surgical career. *Infect Control Hosp Epidemiol*, 11, 243–347.

Melhado M, Hensen J L M and Loomans M (2006). Literature review of staff thermal comfort and patient 'thermal risks' in operating rooms, Proceedings of the 8th International Healthy Buildings Conference, 4–8 June, Lisbon, ISIAQ, pp. 11–14.

Mondal S (2008). Phase change materials for smart textiles – An overview. *Appl Therm Eng*, 28, 1536–1550.

Mora R, English M J M and Athienitis A K (2001). Assessment of thermal comfort during surgical operations. *ASHRAE Transactions* 107(1), 52–62.

Olesen B W and Bovenzi M (1985). *Assessment of the Indoor Environment in a Hospital*, in Clima 2000, Copenhagen, pp. 195–200. Available at http://hero/epa/gov/index.cfm?action=search.view&reference_id=22999

Parsons K C (1993). *Human Thermal Environments*. 2nd edition, Taylor and Francis, London.

Pilcher J J, Nadler E and Busch C (2002). Effects of hot and cold temperature exposure on performance: a meta-analytic review. *Ergonomics*, 45, 682–698.

Pissiotis C A, Komborozos V, Papoutsi C and Skrekas G (1997). Factors that influence the effectiveness of surgical gowns in the operating theatre. *Eur J Surg*, 163, 597–604.

Quebbeman E J, Telford G L, Hubbard S, Wadsworth K, Hardman B, *et al*. (1991). Risk of blood contamination and injury to operating room personnel. *Ann Surg*, 11, 614–620.

Rajendran S and Anand S.C (2003). *Development in Medical Textile*. The Textile Institute, Manchester, UK.

Rigby A J, Anand S C and Miraftab M (1994). Medical textiles. *Knitting Int*, 101, 39–42.

Rutala W A and Weber D (2001). A review of single-use and reusable gowns and drapes in health care. *Infect Control Hosp Epidemiol*, 4, 248–257.

Slater K (1985). *Human Comfort*. Thomas Springfield, USA.

Smith R M and Rae A (1975). Thermal comfort of patients in hospital ward areas. *Ann Occup Hyg* 17(3–4), 303–313.

© Woodhead Publishing Limited, 2011

Song G (2007). Clothing air gap layers and thermal protective performance in single layer garment. *J Ind Textile*, 36(3), 193–205.

Stanley L (1994). OSHA ruling still causing shifts in surgical gown marketplace. *Health Ind Today*, November.

Sudoł-Szopińska I and Tarnowski W (2007). Thermal comfort in the operating suite. *New Med*, 10(2), 40–46.

Suprun N, Vlasenko V and Ostrovetchkhaya Y (2003). Some aspects of medical clothing manufacturing. *Int J Clothing Sci Technol*, 15(3/4), 224–230.

Wilczynska U, Szeszenia-Dabrowska N and Szymczak W (2006). Occupational diseases in Poland, 2005. *Medycyna Pracy*, 57, 225–234.

Wong D A, Alexander J A and Kay L (1998). Risk of blood contamination of health care workers in spine surgery: a study of 324 cases. *Spine*, 23, 1261–1266.

Wong T K S, *et al.* (2004). Effective personal protective clothing for health care workers attending patients with severe acute respiratory syndrome. *Am J Infect Control*, 32(2), 90–96.

Woods J E, Braymen D T, Rasmussen R W, Reynolds G L and Montag G M (1986). Ventilation requirements in hospital operating rooms – part I: Control of airborne particles. American Society of Heating, Refrigerating and Air-conditioning Engineers Inc., (ASHRAE) *Transactions* 92(2A), 396–426.

Wyon D P, Lidwell O M and Williams R E O (1968). Thermal comfort during surgical operations. *J Hygiene*, 66(2), 229–248.

© Woodhead Publishing Limited, 2011

9

Contact sensations of medical textiles on the skin

V. T. BARTELS, Bartels Scientific Consulting GmbH, Germany

Abstract: A variety of medical textiles are used in direct skin contact. The construction and properties of these textiles directly influence their skin irritating potential but also how comfortable they feel to the wearer. Comfortable sensation, such as smoothness and softness, are generated by medical textiles which have a slightly hairy surface, a three-dimensional structure at the side which is in contact with the skin and a slight stiffness. Uncomfortable sensations, such as scratchiness, are caused by inflexible protruding fibre ends and stiff textile constructions such as tightly woven fabrics or insufficiently coated/laminated materials. Textiles with a planar inner surface can cause a strong clinging feeling on sweat-wetted skin. The skin contact properties of medical textiles can be measured using test instruments, which are related to the different sensations. In many instances, however, the textile constructions with good skin contact properties cannot be used as medical textiles since they lack the necessary medical or protective requirements.

Key words: skin contact, contact sensations, skin sensorial comfort, softness, smoothness, scratching, clinging, skin irritations, medical textiles.

9.1 Introduction

Medical textiles, which are in direct contact with skin, have to be skin friendly. This includes not only the absence of harmful substances, but also proper mechanical contact properties with the skin (Pan *et al*., 2005). This chapter deals with these mechanical, 'skin sensorial' properties, the sensations they cause and investigates how textiles can be improved accordingly. Some of these properties can now be measured using laboratory apparatus (Mecheels, 1982, 1998; Bartels and Umbach, 2002a,b).

9.1.1 Overview of chapter

The first section of this chapter is an introduction to the topic of skin sensorial properties. It begins with a look at the diversity of applications for which textiles with skin sensorial properties are necessary before going on to examine the importance of these properties for the user's well-being and comfort as well as for their acceptance of the textile product. The section concludes with a comparison between skin sensorial comfort and fabric hand.

In the second section of this chapter, different scenarios involving contact between textiles and skin are studied and the sensations experienced by the individuals using them are discussed. These include softness, sleekness/roughness, scratching, stiffness, clinging, influence of moisture, initial temperature sensation and finally reddening of skin.

© Woodhead Publishing Limited, 2011

The third section of the chapter contains guidelines and offers advice on how to improve the skin sensorial properties of textiles in general. The fourth section transfers this knowledge to medical applications. The examples given include the varying requirements for nurses' clothing, operating room (OR)-protective clothing, incontinence products, bandages, bed linen and clothing for patients with impaired skin (wounds, atopic eczema).

This chapter ends with a discussion of potential future trends in medical textiles for skin contact, a conclusion in the form of a recapitulatory table and finally offers details of some sources of further information and advice.

9.1.2 Medical textile applications in skin contact

In principle, all textiles that are in direct contact with human skin should be optimised for the 'skin–textile interface' (Mecheels, 1982, 1998; Bartels and Umbach, 2002a,b; Pan *et al*., 2005). This is particularly relevant in the field of medical textiles, where it is necessary in numerous applications:

- *Occupational clothing*: clothing for nurses, doctors, cleaning staff, kitchen employees and caretakers
- *Protective clothing*: OR-protective apparel, germ and body-liquid protective clothing used in pharmacies and laboratories, gloves and face masks
- *Incontinence and hygiene products*: Diapers, adult incontinence and feminine hygiene
- *Bandages* for treatment of e.g. injuries of ligaments and muscles, drainage of lymph fluid or wound care
- *Bed linen* for patients' beds and coverings of examination areas
- *Other textiles*, which are worn on the skin, with a medical function like clothing for people with atopic eczema, bio-functional textiles, smart clothing and drug releasing textiles.

Several of these examples are discussed in detail in Section 9.4.

9.1.3 Importance of mechanical skin contact

The importance of the mechanical skin contact properties of textiles and their impact on the wearer is often underestimated. The term 'skin sensorial comfort' comprises much more than simply the well-being of the wearer:

- *Prevention of mechanical skin irritations*. Textiles with poor skin contact properties may cause skin irritations like reddening (erythema), maceration or prickling.
- *Wear comfort aspect*. In some medical textile applications it is the skin sensorial comfort, which makes the biggest difference to wearers between the various available products. One excellent example is that of medical staff's occupational clothing. When compared to pure cotton garments, cheap and

© Woodhead Publishing Limited, 2011

poorly constructed polyester–cotton blend garments are often rejected by wearers, mainly because of the unpleasant feel of them when in contact with the skin. Although excellent blended fabrics are available on the market, these cheap and inadequate constructions severely impede the acceptance of any blended fabrics by hospital staff.

- *User acceptance*. The examples of medical staff's occupational clothing shows how important the skin sensorial comfort of a textile is for user acceptance, a point which is further proved by the example given in Section 9.1.2. In several cases new textiles had to be bought because patients or staff did not accept the poor skin contact properties of the cheap constructions, previously purchased.

These topics are covered in more detail in Chapter 10 (by Wollina) and Chapter 11 (by Weckmann) of this book. Chapter 10 discusses mechanical skin irritations whereas Chapter 11 deals with allergies. A further reading of these chapters is strongly recommended.

9.1.4 Distinguishing from fabric hand

The terms 'skin sensorial comfort' and 'fabric hand' are often confused or used synonymously. They do, however, have different meanings which are explained and defined in the following:

- *Skin sensorial comfort* in this work denotes the skin contact properties and contact sensations of a textile, which is worn on the skin for a relatively long period of time (hours) and usually on larger areas of the body.
- *Fabric hand* is another important factor in fabric contact. It indicates the sensations felt upon touching the textile by hand, usually for a very short time (seconds). Fabric hand is crucial for the purchase decision. In a shop, for example, textiles with a poor fabric hand would not be bought.

Both skin contact parameters, skin sensorial comfort and fabric hand, are of great importance, but differ substantially in nature. Whereas skin sensorial comfort describes the sensations resulting from long periods of wearing the textile on the body, fabric hand sensations are decided after simply touching a textile with the hand for mere seconds.

This difference is also important for the testing aspect. The well-known Kawabata evaluation system (KES) is designed to measure fabric hand (Kawabata, 1998; NC State University, 2010). Thus, this apparatus is not made for testing the skin sensorial comfort, although some of the tests performed are quite similar.

9.2 Skin contact sensations

It is, to some extent, quite astonishing that humans have skin contact sensations at all. The external layer of skin, the stratum corneum, consists of dead, horny cells (Wollina *et al*., 2006; and Chapter 10). It is therefore interesting that we still

© Woodhead Publishing Limited, 2011

possess such strong tactile senses. The explanation is that the sensation of touch is registered by sensors, which are located in the deeper tissue of the skin.

Usually, however, we do not register the feelings of textile skin contact. As with many other aspects of comfort, a good textile/skin sensorial comfort is characterised more by a non-perception. Generally, we do not recognise the importance of the textile skin interface until problems occur. Perhaps best known of these problems is the so-called wool prickle (Garnsworthy *et al*., 1968).

Of the few positive skin contact sensations, which we feel immediately, two of the most important are the senses of softness and cuddliness. We even go so far as to actively seek these sensations on occasion. Another important skin contact sensation is the temperature of a fabric during skin contact, particularly if a fabric feels warm or cool.

In the following sub-sections, several skin sensorial contact sensations are discussed in more detail. Mainly healthy skin is considered here, except for a few words on atopic eczema and wounds. These aspects are dealt with more precisely in Chapter 2 (Rajendran and Anand) and Chapter 12 (Hipler and Wiegand) of this book.

9.2.1 Softness

One of the most prominent and most desired skin contact properties is softness. This, however, is not a well defined parameter. It is necessary to distinguish between the softness of the fabric as a whole and the softness of the surface.

The softness of the fabric comprises the material's bending characteristics in all directions. In this way, softness is the opposite of stiffness, which is described in Section 9.2.4. Woven and nonwoven fabrics are usually less soft than knitted textiles which are usually more flexible. By this standard woven and nonwoven fabrics should therefore be as flexible as possible to be comfortable but it is possible to go too far the other way, some knitted textiles have been deemed too supple to be comfortable by wearers who felt the fabric was then floppy. There is then an ideal level of flexibility for a fabric to the appropriate level of softness.

The softness of the surface deals with the fibres and yarns, which protrude from the surface. This depends on:

- The number of fibres and yarns above the textile bulk
- The length of the fibre ends
- The bending characteristics of the fibre ends.

Given these parameters, surface softness can be considered the opposite of surface scratchiness (Section 9.2.3).

In order to feel soft, a surface should be hairy and the protruding fibre ends should be easily bendable. An excellent example of this is a fleece. The pile gives a perfect surface for soft sensations.

© Woodhead Publishing Limited, 2011

In clothing, it is not only the textile itself which is important for both aspects of softness, the bending properties and surface characteristics of a material can also depend on embellishments, embroidery, seams, zippers, etc. With these additions it is not only the bending and surface properties which are important, but also their position. For example, stiff materials like zippers cannot be placed in areas of the clothing which are liable to be bent rigorously.

9.2.2 Sleekness/roughness

In direct skin contact, textile surfaces cannot only be felt as soft or scratchy, but also as sleek or rough. Interestingly, sleek textile surfaces are not necessarily felt to be more comfortable than the rougher ones. The sensation of sleekness or roughness is a matter of the 'topography' of the textile's surface, which we can feel with our skin. Depending on the body part, this sensation becomes more or less exact; e.g. the fingertips are more sensitive than the back.

Another way of feeling sleek or rough textiles is via friction (Pan *et al*., 2005). If the textile and the skin move against each other in direct contact, effects like gliding or sticking take place. Often, it is more comfortable if a textile tends to stick slightly at the skin, but if the wearer requires greater movement in his clothing or if the clothes are to be put on, then a gliding textile is preferred. In the latter case, there is an ergonomic advantage to a textile which will glide more easily. Thus, in this application, there is a conflict between the ergonomic properties of the textile and the skin sensorial requirements.

9.2.3 Scratching

The sensation of scratchiness is very much linked to the fibres and yarns, which emerge from the textile's surface. As mentioned in Section 9.2.1, scratching is the opposite of surface softness and depends on the number, length and stiffness of the protruding fibre ends (Naylor and Phillips, 1997). If a textile feels scratchy, it is likely that the fibre ends are too stiff as, for example, in wool prickle (Garnsworthy *et al*., 1968; Li, 1998; Gehui *et al*., 2003). Another source of scratchy sensations is dependent on the cut of the clothing, such as misplaced zippers in direct skin contact (e.g. at the chin) or seams, which are pressed into skin or rubbed against it.

9.2.4 Stiffness

The sense of stiffness is the opposite to the sensation of softness of the fabric (see Section 9.2.1). Stiffness strongly depends on the bending properties of a textile in different directions (e.g. weft/warp or inside/outside direction). A stiff textile shows a high force against bending, whereas a soft or even limp textile causes a small counteraction against a bending force.

© Woodhead Publishing Limited, 2011

9.2.5 Clinging

A clinging sensation from a textile to the skin is a sensation usually caused when skin is sweat wetted. A clinging feeling is considered to feel very uncomfortable because, amongst other reasons, it signals to the brain that we are sweating. Textiles can either glide over the skin or stick to it. Interestingly, textiles which glide are more often felt to be clingy than ones which stick to the skin (Mecheels, 1982). The friction between fabric and sweaty skin should therefore be high.

Skin has to be sweat-wetted before we feel a textile as clingy. Thus, the perception of clinging is more important for textiles that are worn while we are sweating, e.g. at elevated temperatures or during increased activity, such as occupational clothing or sportswear.

9.2.6 Influence of moisture

Apart from clinging, moisture generally influences the skin sensorial comfort negatively. Skin can be moistened by sweat, but also by body liquids like urine or saliva. The moisture has several negative impacts on the skin:

- The moisture leads to a decreased resistance against skin abrasion, meaning that maceration can take place.
- The usual 5.5 pH-value of the skin is destroyed.
- In the wet climate bacteria can grow faster so the risk of infection increases.

Moist skin should therefore be avoided, but, when it does happen, it is important that liquids like sweat or urine are drawn away from the skin and soaked up by the textile. Ideally, the liquid is released into the environment (or the micro-climate to the next clothing layer) or at least stored away from skin.

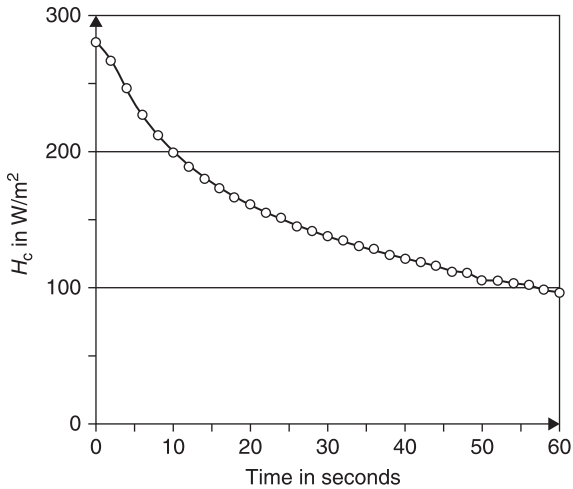
Conversely, an important way to keep skin dry is the transportation of water vapour. This breathability has to be effective enough that perspired sweat does not condense on the skin or textile, but instead diffuses into the environment.

9.2.7 Initial temperature sensation

Upon first touching a textile, a temperature sensation for the contact area occurs. A textile may feel either warm or cool. The highest heat flux between fabric and skin occurs when the skin first touches the fabric (Bartels, 2006b). An initial temperature sensation can occur not only when touching a fabric with the hand, but also when touching fabrics with other parts of the body (even though there are differences in thermal sensitivity, Nadel *et al*., 1973). For example, a pillow will lead to an initial temperature feeling in the face each time we move our head. An exemplary time dependent run of a heat flux curve is given in Fig. 9.1.

Whether a cool or warm temperature sensation is more comfortable depends on the thermoregulatory status of the person, which itself is influenced by ambient

© Woodhead Publishing Limited, 2011



9.1 Initial temperature sensation on pillows. Time dependent heat flux, H_c, between a pillow and a simulated head equipped with heat flux sensors. The higher the heat flux the cooler the initial temperature sensation. At beginning of the experiment, the surface temperature of the pillow was 20°C, the head's temperature 35°C (data taken from Bartels, 2006b).

climatic conditions, workload and clothing. If a person feels cold, e.g. in winter, a warm initial temperature sensation is preferred; but when feeling hot, e.g. during summer, a cool initial temperature sensation is preferred.

9.2.8 Reddening of skin/erythema

If a textile is considerably stiff or rough, it may lead to a reddening of the skin (erythema), often combined with itching. Again, wool prickle is the best known example (Garnsworthy *et al*., 1968). If erythema occurs it is clear warning sign that the skin contact properties of the textile are poor. In medical applications like bandages or medical staff's occupational clothing, textiles are worn on the skin for a long time, which increases the chances of developing erythema. Mechanically induced skin irritations are comprehensively reviewed by Wollina in Chapter 10 of this book.

9.3 Textile properties influencing skin contact sensations

9.3.1 Hairiness

One important contributory factor to the skin contact properties of a textile is its surface hairiness (Mecheels, 1982, 1998). This hairiness depends on the number

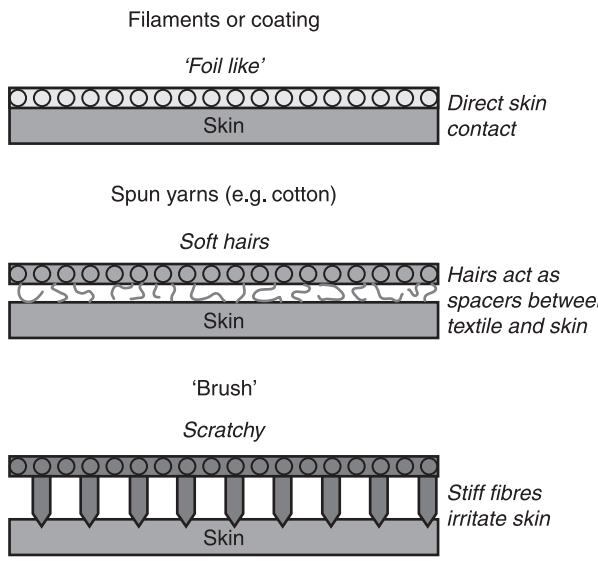
© Woodhead Publishing Limited, 2011

and the length of those fibres and yarns which protrude from the textile bulk. Hairiness makes a great difference to skin contact sensations like whether a fabric feels soft, rough or clingy.

Textiles can vary considerably in their hairiness from material which has no hairs at all, such as fabrics made from filaments, to fabrics with long and stiff fibre ends such as coarse wool. In between there is the optimum hairiness defined as a material with fibre ends, which are soft and easy to bend. Cotton fabrics often fulfil this requirement.

It is worth discussing how the number, stiffness and length of the fibre ends influence the skin contact properties of the textile:

- *Fibre number*. If no fibres are present, the textile bulk lies directly on larger areas of the skin, as illustrated in Fig. 9.2. As a consequence, this type of textile often feels clingy and clammy. On the other hand, long and very stiff fibres emerging from textile's bulk (like a brush) feel scratchy. The most comfortable fabric then has some fibres protruding from the bulk which act as buffers between the skin and the textile. The number of emerging fibre ends has to be large enough so that they can create a space between the fabric and the skin, too few fibres would collapse under pressure, but not so many or so long that the fabric begins to feel scratchy.



9.2 Visualisation of how the skin contact properties depend on fibre ends protruding from the textile bulk. Top: A sleek surface of a micro-fibre or coated fabric. Middle: Soft hairs from spun yarns. Bottom: Stiff, coarse fibre ends can pierce into skin.

© Woodhead Publishing Limited, 2011

- *Fibre stiffness*. Fibre stiffness is a very important factor in creating a scratchy and itchy sensation (Garnsworthy *et al*., 1968; Li, 1998; Gehui *et al*., 2003). From looking at wool we know that coarse fibres with a greater diameter, which are comparably stiff, cause wool prickle. Better wool qualities from finer, thinner and thus softer fibres do not cause a prickle. This principle is the same in other fibrous materials, too.
- *Fibre length*. The length of fibres and yarns, which protrude from the textile bulk, can also have an influence on the sensation of softness or scratching. If a certain fibre is comparatively long, it can be bent much more easily than a shorter fibre of the same type and titre (Schreiber, 2008, 2009). Thus, in comparison to long fibres, short fibres penetrate the skin more often and cause skin irritations. Fibre length can vary over the lifetime of a textile. For example, in polyester–cotton blends used as medical staff's occupational clothing, the yarns and fibres at the surface become shorter during their lifespan, eventually they have sharp broken ends (Höfer, 2008). Consequently, the clothing feels more and more scratchy over time and can even begin to cause skin irritations.

One constructional parameter, which influences the eventual hairiness of a fabric, is the type of yarn used. As previously mentioned, filament yarns exhibit no hairiness at all whereas spun yarns contain numerous hairs, some of which finally protrude from the textile bulk (see Fig. 9.2). In between these extremes, we find textured yarns (Stahlecker, 2003).

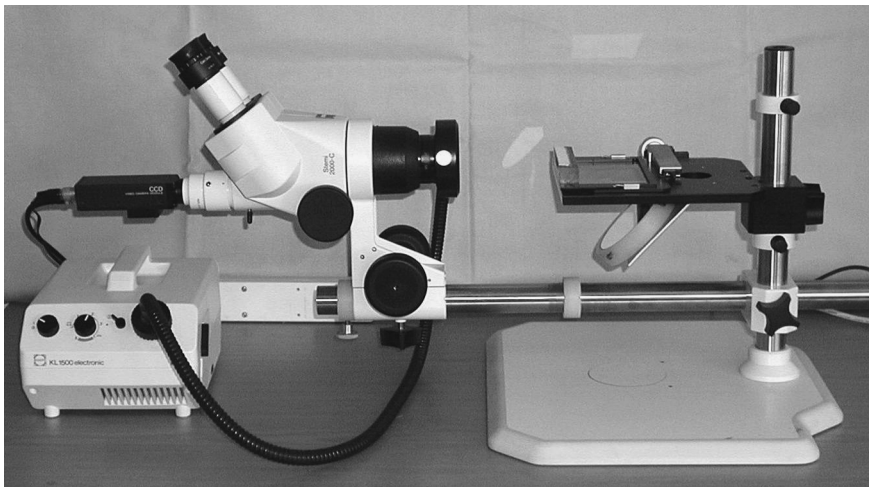
Hairiness can be measured in the laboratory. One method makes use of a laser beam, which targets the textile surface at an angle (Issa *et al*., 2006; Broega *et al*., 2006). The back-scattered light is investigated and provides the information on the textile hairiness.

Another method uses a macro-lens, which views the profile of the textile. This method was first used in the 1980s, when a photo film camera was used (Mecheels, 1982); today digital camera technology is available instead (Bartels, 1999a; see Fig. 9.3). All fibres, which emerge from the textile and are in the region of the depth of field, can be analysed from the image. The analysis shown in Fig. 9.4 reveals the distribution and number of fibres as well as their distance from the textile bulk.

This method can also be used to evaluate fibre stiffness. The textile profile, including all emanating fibres, is placed under pressure; this is most easily achieved by placing a thin plate on top of the textile (Bartels, 1999b). The size of sample and plate are kept identical, meaning that the pressure achieved depends on the weight of the plate. The greater the difference between the sample without pressure and with pressure, the softer the hairs. A hard brush, however, would show no difference between the measurements with or without pressure. This method of characterising the stiffness of hairs can be considered integral since the fibres act together to counterpart the pressure.

An alternative method of testing fibre stiffness is to investigate single fibres (Schreiber, 2008, 2009). It is extremely difficult to measure such small bending

© Woodhead Publishing Limited, 2011



9.3 Apparatus for testing a textile's hairiness. A textile strip is placed as its profile in front of a horizontally mounted microscope with digital camera (Bartels, 1999a).

force as that exerted by a single fibre. The author overcame this problem by deflecting a vertical wire with the fibre. The resultant tension variation is detected using a precision scale. In addition, the preparation of samples when using this method is laborious, as single fibres have to be placed accurately in the sample holder, but well defined bending properties of the fibres themselves are obtained.

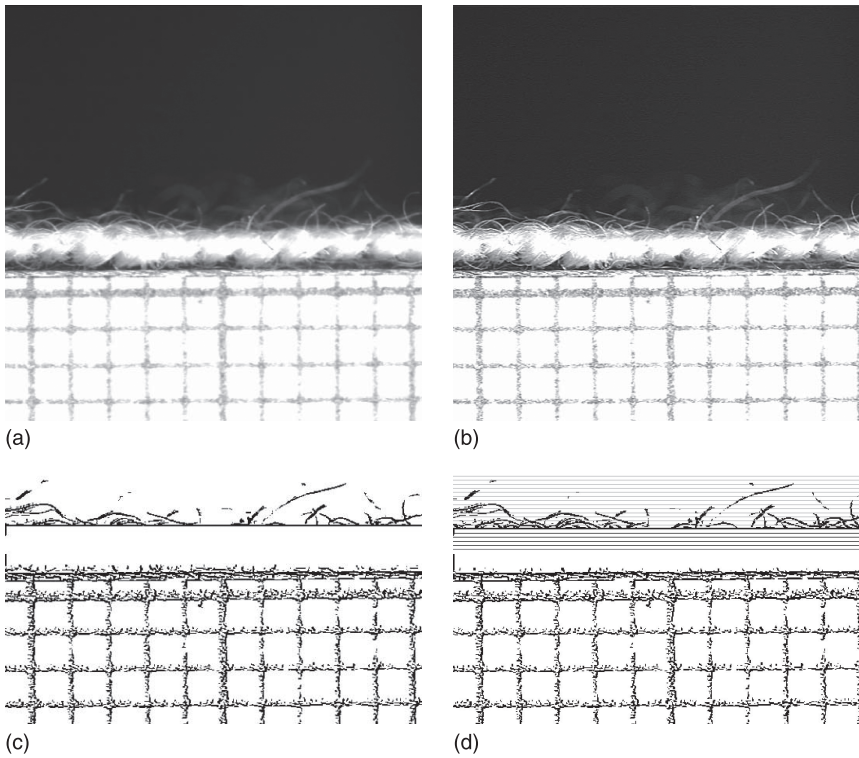
The methods for characterising hairiness discussed so far were quantitative, but one qualitative procedure has to be mentioned too; for example, examination using a microscope or even an electron microscope (Abu-Rous *et al*., 2006). Their images of the textile surface can help to visualise and therefore better understand the situation. For example, one can view broken fibres, which are important in assessing the scratchiness of a fabric (Höfer, 2008).

Conflicts can occasionally arise between the hairiness of a textile and other important parameters, particularly in medical applications. For example, a hairy surface feels comfortable, but:

- It enables pilling and linting
- Putting on clothing takes longer, due to higher friction
- In trousers a sleek surface is better for moving.

Thus, for each application it is necessary to decide which property is more important based on the intended use of the textile and to prioritise accordingly when choosing the optimal textile construction.

© Woodhead Publishing Limited, 2011



9.4 Image analysing process to obtain length and number of fibre ends protruding from the textile bulk. (a) Original photo from the digital camera. (b) Enhancing contrast via a sharpness correction. (c) Digitising the protruding fibres. (d) Putting horizontal lines into the digitised image. From the intersections between horizontal lines and (digitised) fibres, one obtains the number of protruding fibre ends at different distances from the textile bulk (Bartels, 1999a).

9.3.2 Skin contact surface structure

Another skin contact property, which has a great influence on the perceived comfort of a textile is its surface structure. Every fabric has a surface with a three-dimensional pattern, which depends mainly on the weaving or knitting construction, but to some extent also on the type of yarn or finishing. The surface structure of a textile is pivotal to whether a textile causes unpleasant sensations such as clamminess or stickiness, which should be avoided to achieve a satisfactory comfort.

Textiles vary significantly in their three-dimensional surface structure. A coating or membrane (Fung, 2002), which lies directly on the skin, is one extreme. Such a material is completely even. Some micro-fibre fabrics are only little more structured and very sleek, too. The other extremes are textiles with large

© Woodhead Publishing Limited, 2011

three-dimensional surface variations, e.g. piqué, loop plush or fleece. A considerable three-dimensional structure can also be obtained with honeycomb or dotted patterns. To feel comfortable on the skin, a textile should have a considerable three-dimensional surface structure; such a pattern minimises the skin contact area leaving the textile feeling less clammy or clingy and more comfortable and pleasant on the skin.

In clothing it is not only the textile itself which is in contact with the skin but also labels, seams, embroidery etc. These additional materials have to be created to be skin friendly too otherwise discomfort can arise and, although the discomfort is located only in this small area, the whole item of clothing may be rejected by the wearer as a result.

Textile surfaces can now be characterised quantitatively in all three dimensions. An exemplary apparatus, which is enabling such tests, projects a set of different stripe patterns on the sample's surface (GFMesstechnik, 2010). By analysing the back-scattered light, the three-dimensional coordinates of the fabric's surface can be calculated.

Although structured surfaces feel more comfortable than sleek ones, manufacturers frequently do not use them in their products. Often they simply do not know about the skin contact properties, but price is also a strong contributory factor as textiles with structured surfaces tend to be more expensive.

9.3.3 Stiffness

As previously mentioned, stiffness is defined by the textile's bending properties. This simple theory becomes more difficult in practice however since it is necessary to clarify in which direction the bending occurs. The 'natural main directions' of a fabric are in warp and in weft directions. But between these perpendicular alternatives, any other angle could be chosen, too. Additionally, we can bend a textile over its outer side (away from the skin) or its inner side (next to the skin).

An easy method to measure the bending properties of textile fibres, and thus the stiffness of the textile, was developed by Mecheels (1982). The testing device is a horizontal pin fixed to a wooden plate with an angle scale. The construction was further developed and now uses laser beam technology (Bartels and Umbach, 2005; see Fig. 9.5), but the measuring principle remains the same; the middle of a well defined stripe of the textile specimen is put on the horizontal pin. The edges of the sample, which are not on the pin, are bent down due to the gravitational force. The bending angle is measured by means of the angle scale and is a direct measurement of a textile's stiffness.

The great advantages of this stiffness measurement technique are that it is cheap, fast, reliable and, last but not least, it correlates to human comfort perceptions. One disadvantage is that the stiffness results are, due to the influence of gravity, dependent on the sample's size and weight.

© Woodhead Publishing Limited, 2011

9.5 Measuring fabric's stiffness. A textile stripe is placed on a horizontal pin. Subsequently, the position of the specimen is detected by a laser beam. The bending angle of the sample is regarded as the fabric stiffness, the greater the bending angle, the stiffer the textile.

An apparatus which overcomes this limitation was presented by Machova *et al*. (2006). Again a sample stripe is investigated, but, in this case, it is fixed in a vertical position with the short edge standing up. This stripe is bent not vertically but horizontally, meaning that the sample is not bent due to gravity, but only due to the mechanical force applied. The result is therefore independent of the textile's weight, but does depend on the specimen size.

Sometimes the so-called 'Cusick drape tester' according to BS 5058 (1973) is employed to assess fabric stiffness. The original construction has been improved by digital analysing techniques (Kenkare and May-Plumlee, 2005). However, this apparatus was designed in such a way that 'a fabric is said to have a good draping quality when the (resultant) configuration is pleasing to an eye' (Bhalerao, 2010). Consequently, Avril and Filmer (2000) discuss several limitations for testing softness or stiffness with the Cusick drape tester.

The stiffness of a textile is dependent on several construction parameters like knitting or weaving, density, finishing, coating/laminating etc. One common rule is that denser textiles are also stiffer; because in denser textiles more yarns have to

© Woodhead Publishing Limited, 2011

be bent, and there is also less space left into which bent yarns could slip. As a result, bending becomes more difficult the denser the textile.

The type of knitting or weaving used on a fabric is important as an indicator of stiffness too. For example, a twill weave fabric is usually less stiff than a plain weave fabric. Even different twill weaves such as 2/1, 2/2 or 3/1 vary in stiffness however. Furthermore, a coated or laminated textile (Fung, 2002; Hall, 2004b) is usually stiffer than the same textile without coating or lamination.

Finishing can also have a significant influence on stiffness. Easy care finishes for example lead to cross-links between the fibres, which cause a greater bending force. Bio-functional finishes based on cyclo-dextrins (Buschmann *et al*., 1998, 2001) cross-link fibres, too, and, thus, may also stiffen the material, particularly if the finish is overdosed.

Nonwoven textiles are often found to have high bending angles, particularly if they are tested according to the above described Mecheels (1982) method. Such results are, to some extent, caused by the light weight of many nonwoven materials which gives them a low gravitational force. It has to be stated, however, that many nonwovens are not ideally suited for direct skin contact. Although diaper manufacturers show that this is manageable, their top-sheets, which are in direct skin contact, are mostly skin friendly.

Smart clothes will revolutionise the field of medical textiles in the future. But it should not be forgotten that many of these new constructions have to be worn in direct skin contact. The stiffness, particularly, can become a problem, as smart clothing can include stiff components like metallic wires or plastic boxes (Bartels, 2004b).

Textile constructions, which reduce stiffness, can conflict with medical needs. A dense or coated fabric is comparatively stiff, but provides better protection against the penetration of bodily liquids and/or germs (Fung, 2002). Thus, often the stiffness of a fabric can only be reduced to a certain extent within the constraints necessary for the required protection level.

9.3.4 Sweat management

As described in Section 9.2.6, the perceived skin contact sensations are strongly dependent on the moisture on the skin. Water concentration should be low; otherwise the textile feels clingy or damp and skin irritations can occur. Thus, it is an important aspect of skin sensorial perceptions that the textile is able to keep skin dry. This ability will be referred to as ‘sweat management’ in the following sections.

Sweat and thus water can appear either as water vapour or as liquid moisture on the skin. Both states of water aggregation show very different properties, meaning that their transport processes also differ significantly (Simile, 2004), but in both cases, the faster the water is transported away from the skin, the better.

© Woodhead Publishing Limited, 2011

Humans produce water vapour all the time, at least a minimum of 30 g/h, because the skin is a slightly permeable membrane for water vapour molecules. As well as this 'insensible perspiration', humans produce a 'sensible perspiration' for thermo-regulation, which can be up to about a kilogram per hour. At the onset of sensible perspiration, sweat is produced in the sweat glands inside the skin. In thin channels between the sweat gland and the skin's surface the water evaporates, which leads to the desired cooling effect. In this moderate perspiration scenario, sweat still appears on top of the skin as water vapour. If a person sweats heavily or if the clothing is not able to transport the water vapour away fast enough, liquid sweat drops occur on the skin. Water vapour can also condense inside the clothing.

Thus, the first necessity for a textile intended to keep skin dry is the ability to transport water vapour properly, a property often described as 'breathability', but which more accurately is water vapour permeability or water vapour resistance. This is crucial not only for the skin sensorial comfort but also for the thermo-physiological comfort (Ruckman, 2005). Physically, water vapour transport is a diffusive process under spatial constraints; these constraints are set by the porosity and thickness of the textile.

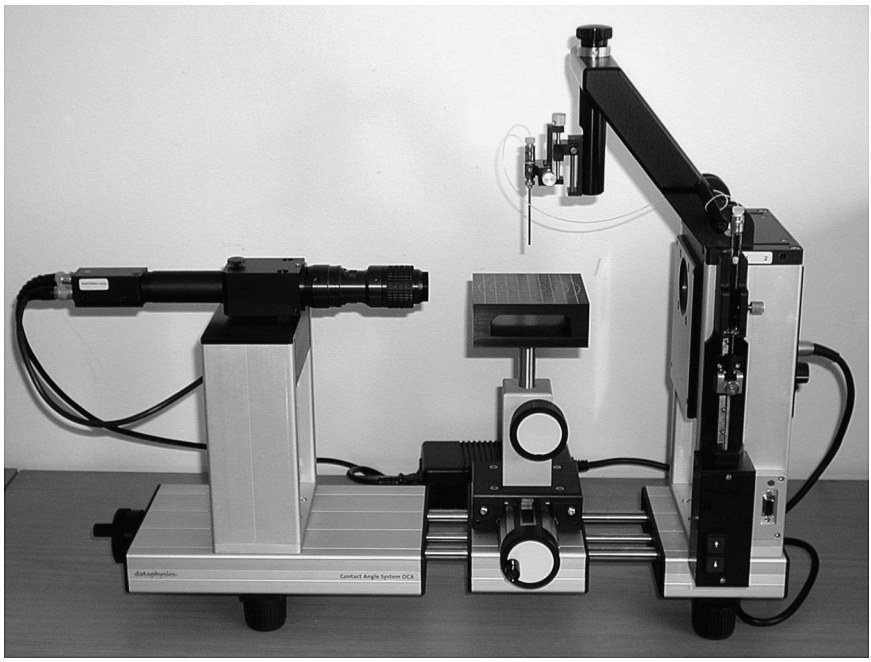
For coated or laminated textiles breathability is one of the decisive quality criterions, as it varies significantly within this group of materials (Träubel, 1999; Fung, 2002; Holmes, 2004; Ruckman, 2005). A good breathability requires more than a water vapour permeable membrane, a good coating or laminating process (Fung, 2002; Hall, 2004b) is also essential. In fact, for the breathability obtained in praxis, proper quality management is even more important than having a certain type of membrane or coating (Bartels, 2010).

If liquid sweat occurs on skin, the textile has to soak it up within a few minutes in order to remain comfortable. The sweat either has to be stored or, even better, be transported through the textile into the environment. In fabrics, liquid water is transported in capillaries between fibres and yarns or is adsorbed at fibres and migrates along them (Mecheels, 1998).

For both the transport and the absorption of liquid sweat the textile should be hydrophilic, i.e. it should have a water wettable surface. This is tested by an apparatus as shown in Fig. 9.6. If not present in the textile already, hydrophilic properties can be achieved using a finish and be regenerated by proper washing procedures.

A hydrophilic finish can impair the protective function of clothing, however, particularly if a repelling of aqueous liquids is desired. Thus, the hydrophilic finish would have a negative effect on the protection against, for example, body liquids or stains. In addition, hydrophilic textiles may need more time for drying and use up more energy in the tumble dryer. Again, one has to check how much comfort (hydrophilic finishing) is achievable within the constraints of the necessary protective and technical needs.

© Woodhead Publishing Limited, 2011



9.6 System for testing the sorption speed of a sweat drop by a textile. A defined drop of water is positioned on the specimen by a hollow needle. The drop is observed by video camera plus macro-lens. Important parameters are, for example, the contact angle or the time span until the drop is completely soaked up.

9.4 Examples of applications

9.4.1 Nurses' occupational clothing

The first medical application for which the importance of the skin contact properties is discussed here is nurses' occupational clothing. This kind of apparel used to be made from cotton for many years. Then, polyester–cotton blends were utilised, which had advantages in price and in laundry costs. With this change from pure cotton to PET/CO 65/35 or PET/CO 50/50 complaints arose from the wearers. Some of these complaints were due to psychological effects as cotton is regarded as a natural product, whereas polyester is synthetic, but many of the complaints were due to the disadvantages of the blended textiles in the field of skin contact properties. Wearers felt that they sweated more easily in their new clothing and that it felt clingy and scratchy.

These skin sensorial disadvantages are typical for low price blended clothing. Cotton usually has a good or even very good skin contact sensation naturally. Blended fabrics, however, have to be constructed accordingly to achieve

© Woodhead Publishing Limited, 2011

comparable skin contact properties. If some constructional guidelines are followed Umbach (1988) claims that a blend can offer the same good contact properties as pure cotton. These guidelines are often neglected, however, due to price reasons, and consequently wearers still complain of discomfort. How a modern nurses' occupational clothing may look is described by Walz in Chapter 21 of this book.

9.4.2 Protective clothing for the operating room (OR)

OR-protective clothing is worn by surgeons and nurses during their work in the operational theatre. Gowns are most frequently worn, but full body covering overalls are used, too. Apart from this 'main' apparel, OR-protective clothing also comprises other clothing items used in the OR, such as face masks or gloves.

Usually OR-protective clothing is constructed to improve protection (Offermann *et al*., 2000) and does not focus on achieving good skin contact properties. For most parts of the body this may be acceptable, as nurses' occupational clothing and some underwear are worn under the gown, and direct skin contact exists only on the lower arms. The lower arms, however, are pivotal in deciding the overall comfort sensation and should be considered accordingly.

From the point of view of skin contact properties, OR-protective clothing is often catastrophic (Bartels, 1999b). Materials are hydrophobic, extremely sleek and lack any considerable surface structure. Thus, the clothes are quickly felt as clinging to skin or being clammy, and the sweat stays on the skin and is not soaked up by the material. The OR-protective textiles are manufactured in this way to optimise their protective or medical properties like repelling body liquids and the prevention of linting.

Nevertheless, some skin sensorial optimisations of OR-protective clothing are achievable. One way is the textile's finish, which is typically hydrophobic to enhance protection (Avril and Filmer, 2000). Manufacturers have now managed to finish a textile so that it is hydrophobic only on the outside and can be hydrophilic on the inside. A hydrophilic lining could be employed under a hydrophobic outer shell in OR-protective clothing then, as in modern foul-weather protective clothing (Bartels, 2006a,d). These techniques combine both, protection outside, and better skin contact properties and sweat uptake inside. The only disadvantage is price.

We know from functional sportswear that three-dimensional surface structures like honeycombs lead to improved skin sensorial comfort (Bartels, 2003a). These constructions are often made from filaments and could be adjusted to the inside of an OR-protective laminate with good linting properties.

9.4.3 Incontinence products

The skin contact properties of incontinence textiles are even more important than for other medical applications:

© Woodhead Publishing Limited, 2011

- Incontinence products are often worn 24 h a day. Incontinence textiles therefore have plenty of time in which to irritate skin.
- Incontinence textiles and the skin below them have to cope with large amounts of moisture.
- The moisture is comparatively aggressive as urine contains several other substances than just water.
- The mechanical abrasion is severely increased if faeces are also present.

It is important therefore for manufacturers of incontinence products to find technical solutions for these skin contact problems. As most incontinence products are disposable, the textiles used are nonwovens, for which similar principles have to be followed as for woven fabrics. On the facing skin side of the incontinence product, this 'top sheet' does not only separate skin from the superabsorbent layer but has to be very skin friendly, too (Bartels, 2007). In terms of nonwovens it has to be a soft material (FiberVisions, 2003). This is achieved by a quite open structure, which is not too entangled, and which also helps to guide urine into the superabsorbent layer. Long and soft (low titre) fibre ends protruding from the textile bulk create a soft surface.

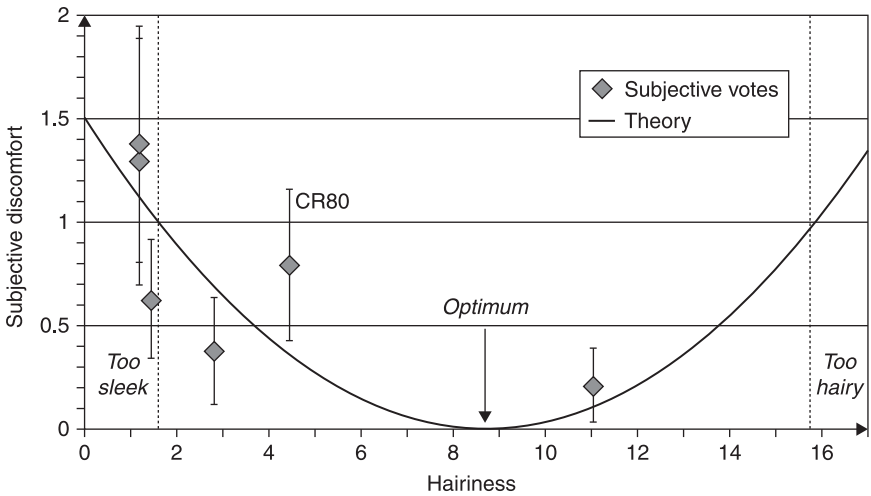
An important point, which should be mentioned here, is the hydrophilic finishing (Hengstberger, 2003; Kang, 2006). It is not only important for a pleasant skin contact, but also for the fast transport of urine into the superabsorbent layer. The 'raw' polypropylene material is not able to manage the moisture, as polypropylene has a hydrophobic surface and repels water. Thus, an effective hydrophilic finishing is required. It has to be durable enough that it stays at the fibre surfaces for the typical lifetime of the incontinence products, which could be at least a whole night or several hours during daytime, sometimes even for several uses (Avril and Filmer, 2000).

9.4.4 Bandages

Another application of medical textiles with respect to skin contact is bandages, as they are used for curing diseases or injuries of ligaments and muscles, which have to be stabilised. Therefore, bandages apply a high pressure on the body, i.e. the skin textile interface of bandages is characterised by a considerably higher pressure than in most other applications. Additionally, as the bandage is in very tight skin contact, all moisture has to be transported through the material.

Interestingly, the general rules for the skin-friendly design of the textile surface remain unchanged. Taking results from wearer trials with human test subjects as well as from laboratory test methods, it turned out that the fabric's hairiness is quite decisive for the subjectively perceived skin sensorial comfort (Bartels, 2000, 2004a). Particularly constructions which were too sleek without protruding fibre ends were rated as poorer by the test subjects than hairier constructions (see Fig. 9.7).

© Woodhead Publishing Limited, 2011



9.7 Discomfort as a function of hairiness. At the *x*-axis the hairiness is given as a parameter obtained via the process shown in Fig. 9.4. The *y*-axis represents the perceived skin sensorial discomfort. The diamonds and error bars represent subjective sensations of test subjects wearing different bandages. A parabolic function ('theory') was fitted to this data. Subjective discomfort values up to 1 relate to small discomfort, which is tolerable. On the other hand, subjective discomfort values greater than 1 are not acceptable. The optimum value for hairiness according to this curve is around 8.7, whereas values < 1.6 or > 15.8 indicate too sleek or too hairy fabrics, respectively (data taken from Bartels, 2000a).

Apart from textiles, bandages are made from foams like neoprene. This material has no water vapour permeability, which leads to a moisture accumulation beneath the bandage and to all the negative skin contact properties mentioned in Section 9.2.6. As bandages are worn the whole day, the skin is moist for hours, an 'optimal' climate for building up skin irritations. As a consequence, manufacturers perforate the neoprene foam and use a cotton lining, both of which help to reduce the moist situation slightly. It has to be stated however that bandages made from textiles like knitted or three-dimensional warp-knitted fabrics (Schlotterer, 2003; Heide and Möhring, 2003) are clearly better alternatives for skin healthiness in comparison to neoprene (Bartels and Umbach, 2000, 2002b; Bartels, 2003b, 2004a).

9.4.5 Bed linen and coverings

Skin contact properties are not only of interest for clothing but also for bed linen and medical coverings used at the patient–device interface, e.g. on examination

© Woodhead Publishing Limited, 2011

tables, chairs, X-ray or tomography. In principle, the aforementioned guidelines for clothing are valid for all these types of applications, too. But it is worth discussing these applications as well in order to have a further look at the temperature sensation on the first skin contact.

During summertime, most people prefer sleek, tightly woven bed linen, because these materials feel cool at first touch (Bartels, 2006b). Some manufacturers even make use of phase-change materials (PCM), which, due to the latent heat necessary to melt the PCM, increases this effect (Bartels, 2006b). On the other hand, during wintertime voluminous and hairy bed linen is more likely to be chosen. This feels warmer at first touch. These constructional principles can be used for bed linen in hospitals as well as for medical coverings.

The temperature sensation on first touch is dependent on the thermal conductivity of the material (PCM: latent heat of phase-change). Sleek and smooth fabrics possess a lower portion of air than hairier textiles. As air is an effective insulator, sleek textiles feel cool whilst hairy ones feel warm. It should be mentioned, however, that the overall thermal insulation of the duvet or the pillow remain relatively unchanged, since these, due to their thickness, contribute much more to thermal insulation than the bed linen.

9.4.6 Impaired skin

New problems can now occur if a textile is in contact with impaired or diseased skin. One example is wounded skin. This important medical textile application is extensively discussed by Rajendran and Anand in Chapter 2 of this book. Wounds need special treatments, very different to the needs of non-injured skin. For example, wounds have to stay a little moist to ensure a successful healing process. Another aspect is the force necessary to remove a plaster or bandage from a wound without injuring it again. These are not factors which need to be taken into consideration for healthy skin.

Another textile application in direct contact with impaired skin is clothing or bed linen for patients with atopic eczema (Diepgen *et al*., 1995; Wollina, 2005; Ricci *et al*., 2006; Diepgen and Schuster, 2006). An extensively studied and successfully practiced approach for this type of clothing is described by Hipler and Wiegand in Chapter 12 of this book. It is based on regenerated man-made cellulose fibres according to the lyocell process. Special treatments based on algae (Zikeli, 2006) and an anti-microbial finish based on silver (Lansdown, 2006) lead to significant improvements of the atopic eczema. Other positive results on the use of similar regenerative (lyocell-type) fibres were reported from Diepgen and Schuster (2006) for the clothing and bed linen of patients with atopic eczema or psoriasis. As an alternative to silver, the antimicrobial effect can also be achieved using chitosan (Knittel and Schollmeyer, 2006). The preferred surface structures of clothing for atopic eczema by patients are usually sleek filament constructions

© Woodhead Publishing Limited, 2011

(Harnisch and Hipler, 2008), sometimes with a silver coating (Haug *et al*., 2006, Gauger, 2006).

9.5 Future trends

It is important that medical textiles continue to become more and more functional. An example is smart clothing, which includes electronic or micro-technical parts. However, these parts can be hard, stiff or water vapour impermeable (Bartels, 2004b). Those components, which are worn directly on the skin, have to be skin friendly otherwise the user acceptance is endangered.

One way to achieve both functionality and skin friendliness, is to use textile integrated components such as sensors, wires or buttons (Lussey, 2006). An example of this future technology is a babygrow which helps prevent sudden infant death developed from Linti and Horter (2009). The skin contact properties of these textile integrated components are much more similar to those of 'normal' fabrics.

Another future trend is that medical textiles will become more specialised. For an increasing number of illnesses or injuries new textiles are being developed. For those materials, which are worn directly on the skin, the contact properties should be considered.

The number of applications for bio-functional medical textiles is still growing, but one has to carefully choose the ingredients as well as the recipes. Surveys revealed that different ingredients and recipes lead to considerable differences in the textile's skin contact properties (Bartels, 2006c). Some finishes maintain the skin sensorial comfort, but others worsen it significantly.

In this manner drug-releasing or cosmetic textiles also have to be considered (see Chapter 6 by Mathis and Mehling, and Chapter 7 by Toti *et al*.). The number of applications these are used in, particularly in the medical field, but also in consumer products, will increase significantly in the future. For these textiles the trend to tailor-made products is very prominent.

For most future trends mentioned so far, textile finishing is an important influence (Hall, 2004a). Finishes become more functional, specialised, bio-functional and release drugs or cosmetics. As an alternative to mainly chemical finishes (Gottwald, 2004) many authors consider plasma treatment as an upcoming tool to obtain tailor-made textile surfaces (e.g. Vesa, 2000).

Last, but not least, price is always an important factor in medicine. A buyer simply searching for the lowest price will never purchase a textile that is optimised for good skin contact properties. However, this may be a dangerous strategy: There are several examples of buying cheap clothing which ended up being more expensive in the long run, e.g. poor quality cheap nurses' occupational clothing was bought but then led to a great discomfort, and consequently the users complained. In several cases the cheap clothing had to be replaced by slightly more expensive but much more comfortable clothing. However, the need to save costs will continue to be strong in future.

© Woodhead Publishing Limited, 2011

9.6 Conclusions

All medical textiles, which are used in direct contact with skin, have to exhibit skin-friendly mechanical properties. In this chapter we described different skin contact sensations, examined how they relate to textile properties and determined which fabric constructions are comfortable. For a detailed overview, the main findings are collected in Table 9.1. Using this knowledge, the skin contact properties of different medical textile products can be significantly improved concerning skin healthiness, comfort and user acceptance.

Table 9.1 Summary of main results

Skin contact sensation	Adverse sensation	Related textile property	Favourable construction
Softness of textile as a whole	Stiffness	Bending angle or bending force	Woven fabrics and nonwovens: Small bending force Fewer yarns Open structure Just slightly entangled Twill instead of plain weave Not coated or laminated Correctly applied finishes Knitted textiles: Small bending force but not supple
of textile surface	Scratching	Hairiness Number of fibres and yarns Length of fibre ends Bending characteristics of fibre ends	Surface with easy bendable hairs Fibre ends with small titre Spun yarns
Sleekness	Roughness	Surface topography Friction between skin and textile	High friction, no gliding Considerable three-dimensional structured surface
Clinging		Friction between sweat wetted skin and textile	High friction between sweat wetted skin and textile
Moisture		Speed of moisture uptake Water-vapour permeability	Fast moisture uptake Hydrophilic finish High water vapour permeability Proper coating or lamination process

© Woodhead Publishing Limited, 2011

Table 9.1 Continued

Skin contact sensation	Adverse sensation	Related textile property	Favourable construction
Initial temperature		Heat flux between textile and skin on first touch	If cool is desired: high heat flux Densely woven Low hairiness If warm is desired: low heat flux Openly structured Hairy
Reddening of skin		Erythema	Small stiffness Small roughness

9.7 Sources of further information

Despite their importance the skin contact properties of textiles are seldom investigated, hence sources of further information are relatively few. Those that do exist are included in the list of references at the end of this chapter and will offer the reader additional material on this topic.

Within this book the following chapters are recommended for a further understanding of the skin contact properties of medical textiles in diverse applications:

- Chapter 2 by Rajendran and Anand on wound care
- Chapter 6 by Mathis and Mehling on textiles with cosmetic effects
- Chapter 7 by Toti *et al*. on drug-releasing textiles
- Chapter 10 by Wollina on mechanical skin irritations
- Chapter 11 by Weckmann on allergies caused by textiles
- Chapter 12 by Hipler and Wiegand on textiles used for patients with atopic eczema
- Chapter 14 by Wiesemann and Adam on incontinence and hygiene products
- Chapter 21 by Walz on nurses' occupational clothing.

These chapters include several interesting aspects of medical textiles in skin contact. Finally the book *Biofunctional Textiles and the Skin*, edited by Hipler and Elsner (2006) is recommended. It includes several additional medical aspects, particularly in the field of atopic eczema.

9.8 Acknowledgment

The author thanks Hohenstein Institutes for their permission to use the photographs in Figs 9.3, 9.4, 9.5 and 9.6.

© Woodhead Publishing Limited, 2011

9.9 References

Abu-Rous M, Ingolic E and Schuster K C (2006). 'Visualisation of the nano-structure of Tencel® (Lyocell) and other cellulosics as an approach to explaining functional and wellness properties in textiles', *Lenzinger Berichte*, 85, 31–37.

Avril D and Filmer K (2000). 'Increased understanding and improvement in the manufacture and testing of spunbond and spunbond composites resulting in enhanced fabric properties', International Conference on Fibrous Products in Medical and Health Care, Tampere, June 12–14.

Bartels V T (1999a). 'Quantitative Erfassung der taktilen Eigenschaften von Textilien in Abhängigkeit von den Konstruktionsmerkmalen der Oberflächenfasern', Technical report No. AiF 11089, Bekleidungsphysiologisches Institut Hohenstein, Bönnigheim, March.

Bartels V T (1999b). 'Erforschung der bekleidungsphysiologischen Anforderungsprofile an Textilien für Krankenhaus-Schutzbekleidung', Technical report No. AiF 11090, Bekleidungsphysiologisches Institut Hohenstein, Bönnigheim, March.

Bartels V T (2000). 'Grundsatzuntersuchung zur physiologischen Funktion von medizinischen Bandagen und Erstellung eines Anforderungsprofils an die dazu verwendeten Textilien', Technical report No. AiF 11283, Bekleidungsphysiologisches Institut Hohenstein, Bönnigheim, March.

Bartels V T (2003a). 'Erforschung der textilen Konstruktionsparameter für innovative Kleidungssysteme für den Bereich Sport und Arbeitsschutz mit verbesserter physiologischer Funktion', Technical report No. AiF 12846, Bekleidungsphysiologisches Institut Hohenstein, Bönnigheim, June.

Bartels V T (2003b). 'Funktionelle Maschenwaren für den Einsatz in medizinischen Bandagen', in Loy W (ed.), *Taschenbuch für die Textilindustrie 2003*, Schiele und Schön, Berlin, pp. 227–234.

Bartels V T (2003c). 'Hydrophil ausgerüstete Futter – Moisture Management von Wetterschutztextilien', *Textilveredlung*, 38(9/10), 8–14.

Bartels V T (2004a). 'Smart Bandages for Orthopedic Support', Medical Textiles 2004, Pittsburgh, 26–27 October.

Bartels V T (2004b). 'The Physiological Function of Intelligent Technical Textiles for Protective Clothing', CINTE Techtextil China Symposium, Shanghai, 31 August–2 September.

Bartels V T (2006a). 'Bekleidungsphysiologische Optimierung von Futterstoffen zur Verbesserung des flüssigen Schweißtransports in wasserdichter Funktionskleidung', Technical report No. AiF 13614 N, Bekleidungsphysiologisches Institut Hohenstein, Bönnigheim, March.

Bartels V T (2006b). 'Thermophysiologische und hautsensorische Grundsatzuntersuchung von Kissen', Technical report No. AiF 14099 N, Bekleidungsphysiologisches Institut Hohenstein, Bönnigheim, October.

Bartels V T (2006c). 'Physiological comfort of biofunctional textiles', in *Biofunctional Textiles and the Skin*', Hipler U C and Elsner P (eds.). Volume 33 of Burg G (ed.), *Current Problems in Dermatology*, Karger, Basel, pp. 51–66.

Bartels V T (2006d). 'Skin sensorial properties of functional lining materials', *Melliand English*, 87(7-8), E127–E128.

Bartels V T (2007). 'Absorbercomposits zur physiologischen Verbesserung von thermoregulatorisch belastender Schutzkleidung', Technical report No. AiF 14310 N, Bekleidungsphysiologisches Institut Hohenstein, Bönnigheim, April.

© Woodhead Publishing Limited, 2011

Bartels V T (2010). 'Buyers' requirements for breathable laminates and coatings', *Tech Textile Int*, 19(3), 33–34.
Bartels V T and Umbach K-H (2000). 'Medical bandages made of textiles have advantages over neoprene', *Melliand English*, 81(10), E214–E216.
Bartels V T and Umbach K-H (2002a). 'Hautkontakt – der hautsensorische Tragekomfort von Sportkleidung auf dem Prüfstand', *Kettenwirk-Praxis*, 36(2), 12–15.
Bartels V T and Umbach K-H (2002b). 'Test and evaluation methods for the sensorial comfort of textiles', Euroforum 'Toucher du Textile', Paris, 4–5 December.
Bartels V T and Umbach K-H (2002c). 'Physiological demands on materials for bandages', 6th Dresden Textile Conference, 19–20 June.
Bartels V T and Umbach K-H (2005). 'New test apparatus to assess the stiffness of clothing textiles', *Melliand English*, 86(11–12), E195–E196.
Bhalerao S V (2010). 'Fabric drape and its measurement', *Indian Textile J*, Available: http://www.indiantextilejournal.com/articles/FAdetails.asp?id=481, accessed 4 Nov. 2010.
British Standard (1973). 'Method for the assessment of drape of fabrics', BS 5058.
Broega A C, Silva C, Ben Said S, Adolphe D, Schacher M E and Schacher L (2006). 'Computational methods in the evaluation of high quality fabric comfort for clothing', International Fiber Conference, Seoul, 30 May–6 June, pp. 471–472.
Buschmann H-J, Denter U, Knittel D and Schollmeyer E (1998). 'The use of cyclodextrins in textile processes—an overview', *J Textile Inst*, 89(Part 1)(3), 554–561.
Buschmann H-J, Knittel D and Schollmeyer E (2001). 'New textile applications of cyclodextrins', *J Inclusion Phenomena Macrocyclic Chem*, 40, 169–172.
Diepgen T L, Salzer B, Tepe A and Hornstein O P (1995). 'Hautreizungen durch Textilien unter standardisierten Schwitzbedingungen bei Patienten mit atopischem Ekzem', *Melliand Textilberichte*, 76(12), 1116–1121.
Diepgen T L and Schuster K C (2006). 'Dermatological examinations on the skin compatability of textiles made from Tencel® fibres', *Lenzinger Berichte*, 85, 61–67.
FiberVisions a/s (2003). 'FiberVisions Spezialfasern: Vorteile für hygienisch-sanitäre und medizinische Vliesstoffprodukte', in Loy W (ed.), Taschenbuch für die Textilindustrie 2003, Schiele und Schön, Berlin, pp. 115–123.
Fung W (2002). *Coated and Laminated Textiles*, Woodhead Publications, Cambridge.
Garnsworthy R K, Gully R L, Kandiah R P, Kenins P, Mayfield R J and Westerman R A (1968). 'Understanding the causes of prickle and itch from the skin contact of fabrics', Technical report No. G64, CSIRO Textile and Fibre Technology, February.
Gauger A (2006). 'Silver-coated textiles in the therapy of atopic eczema', In *Biofunctional Textiles and the Skin*, Hipler U C and Elsner P (eds.), Volume 33 of Burg G (ed.), *Current Problems in Dermatology*, Karger, Basel, pp. 152–164.
Gehui W, Postle R and Weiyuan Z (2003). 'The prickle of worsted woven wool fabrics', *Textile Asia*, 34(3), 25–28.
GFMesstechnik (2010). Available: http://www.gfmesstechnik.de/index.php?lang=en [accessed 9 November 2010].
Gottwald P (2006). 'Ausrüstung von Technischen Textilien', In *Technische Textilien*, Knecht P (ed.), Deutscher Fachverlag, Frankfurt, pp. 67–81.
Hall M E (2004a). 'Finishing of technical textiles', In *Handbook of Technical Textiles*, Horrocks A R and Anand S C (eds.), Woodhead Publications, Cambridge, pp. 152–172.

© Woodhead Publishing Limited, 2011

Hall M E (2004b). 'Coating of technical textiles', In *Handbook of Technical Textiles*, Horrocks A R and Anand S C (eds.), Woodhead Publications, Cambridge, pp. 173–186.

Harnisch M and Hipler U C (2008). 'Kleidung für Menschen mit Neurodermitis oder Psoriasis', Technical report No. AiF 14712 BG, Bekleidungsphysiologisches Institut Hohenstein, Bönnigheim.

Haug S, Roll A, Schmid-Grendelmeier P, Johansen P, Wüthrich B, *et al*. (2006). 'Coated textiles in the treatment of atopic dermatitis' In *Biofunctional Textiles and the Skin*, Hipler U C and Elsner P (eds.) Volume 33 of Burg G (ed.) '*Current Problems in Dermatology*', Karger, Basel, pp. 144–151.

Heide M and Möhring U (2003). 'Fertigung und Eigenschaften von Abstandsgewirken für medizinische Verwendungszwecke', in *Taschenbuch für die Textilindustrie 2003*, Loy W (ed.), Schiele und Schön, Berlin, pp. 251–262.

Hengstberger M K (2003). 'Finish for high absorption nonwovens', 42nd International Man-Made Fibres Congress, Dornbirn, 17–19 September.

Hipler U C and Elsner P (eds.) (2006). 'Biofunctional Textiles and the Skin', Volume 33 of Burg G (ed.), '*Current Problems in Dermatology*', Karger, Basel.

Höfer D (2008). 'Untersuchung zur Beseitigung mechanisch ausgelöster Hautirritationen durch textile Gewebe', Technical report no. AiF 14655 N, Bekleidungsphysiologisches Institut Hohenstein, Bönnigheim.

Holmes D A (2004). 'Waterproof breathable fabrics', In *Handbook of Technical Textiles*, Horrocks A R and Anand S C (eds.), Woodhead Publications, Cambridge, pp. 282–315.

Issa M, Strazdiene E, Gutauskas M, Valatkiene L, Schacher L and Adolphe D (2006). 'Fabric weave type: Dependencies between sensory analysis and instrumental evaluation', International Fiber Conference, Seoul, 30 May–6 June, pp. 239–240.

Kang I S (2006). 'Effect of hydrophilic and hydrophobic finishes on surface characteristics of polyester fabric', International Fiber Conference, Seoul, 30 May–6 June, pp. 737–738.

Kawabata S (1998). 'My Research Life', *Textile Asia*, 29(9), 53–54.

Kenkare N and May-Plumlee T. 'Fabric drape measurement: A modified method using digital image processing', *J Textile Apparel, Technol Manage*, 4(3), 1–8.

Knittel D and Schollmeyer E (2006). 'Chitosans for permanent antimicrobial finish on textiles', *Lenzinger Berichte*, 85, 124–130.

Lansdown A B G (2006). 'Silver in health care: Antimicrobial effects and safety in use', In *Biofunctional Textiles and the Skin*, Hipler U C and Elsner P (eds.), Volume 33 of Burg G (ed.) '*Current Problems in Dermatology*', Karger, Basel, pp. 17–34.

Li Y (1998). 'Wool sensory properties and product development', *Textile Asia*, 29(5), 35–39.

Linti C and Horter H (2009). '*Baby Body – Textilien retten Leben*', Institut für Textil- und Verfahrenstechnik, Denkendorf.

Lussey D (2006). 'Softswitch technology riding a second wave', *Tech Textiles Int*, December 2008, p. 42,.

Machova K, Klug P, Waldmann M, Hoffmann G and Cherif C (2006). 'Determining of the bending strength of knitted spacer fabrics', *Melliand English*, 87(6), E93.

Mecheels J (1982). 'Zur Komfort-Wirkung von Textilien auf der Haut', Hohensteiner Forschungsbericht, Bekleidungsphysiologisches Institut Hohenstein, Bönnigheim, April.

Mecheels J (1998). 'Körper – Klima – Kleidung – Wie funktioniert unsere Kleidung?', Schiele und Schön, Berlin.

Nadel E R, Mitchell J W and Stolwijk J A J (1973). ' Differential thermal sensitivity in the human skin', *Pflügers Archiv*, 340, 71–76.

© Woodhead Publishing Limited, 2011

Naylor G R S and Phillips D G (1997). 'Fabric-evoked prickle in worsted spun single jersey fabrics', *Textile Res J* 67(6), 413–416.

NC State University (2010). 'Fabric hand lab', Available: http://www.tx.ncsu.edu/tpacc/comfort/fabric_hand_lab.html [accessed 8 November 2010].

Offermann P, Aibibu D and Mägel M (2000). 'Evaluation and testing of optical test methods for the geometric analysis of the pore spaces of operating room and hospital textiles', International Conference on Fibrous Products in Medical and Health Care, Tampere, June 12–14.

Pan N, Zhong W, Maibach H and Williams K (2005). 'Fabric and skin: Contact, friction and interactions', Technical report, NTC-project S05-CD04.

Rajendran S and Anand S C (2011). 'Hi-tech textiles for interactive wound therapies', Chapter 3 of this volume.

Ricci G, Patrizi A, Bellini F and Medri M (2006). 'Use of textiles in atopic dermatitis', In *Biofunctional Textiles and the Skin*, Hipler U C and Elsner P (eds.), Volume 33 of Burg G (ed.) '*Current Problems in Dermatology*', Karger, Basel, pp. 127–143.

Ruckman J E (2005). 'Water resistance and water vapour transport', In *Textiles in Sport*, Shishoo R (ed.). Woodhead Publications, Cambridge, pp. 287–305.

Schlotterer H (2003). 'Fertigungstechniken der Flachstrickmaschine im medizinischen und sanitär-medizinischen Sektor', In *Taschenbuch für die Textilindustrie 2003*, Loy W (ed.). Schiele und Schön, Berlin, pp. 212–226.

Schreiber H (2008). 'Untersuchung zur Beseitigung mechanisch ausgelöster Hautirritationen durch textile Gewebe', Technical report no. AiF 14655 N, Institut für Textil- und Verfahrenstechnik, Denkendorf.

Schreiber H (2009). 'Textilien als Ursache mechanischer Hautirritationen', Denkendorfer Innovationstag, 5 March.

Simile C (2004). 'Critical evaluation of wicking in performance fabrics', Master's thesis, Georgia Institute of Technology.

Stahlecker S (2003). 'Unterschiedliche Garnstrukturen dank neuester Textiltechnologien', In Taschenbuch für die Textilindustrie 2003, Loy W (ed.). Schiele und Schön, Berlin, pp. 143–148.

Träubel H (1999). *New Materials Permeable to Water Vapor*, Springer, Berlin.

Umbach K-H (1988). 'Workwear from blended fabrics with good wear comfort', *Melliand English*, 69, E343–E347.

Vesa P (2000). 'Improving polyester fabric sorption by low-temperature/low-pressure plasma treatment', International Conference on Fibrous Products in Medical and Health Care, Tampere, June 12–14.

Wollina U (2005). 'Spezielle Anforderungen der sensitiven und der Ekzemhaut an Textilien', Welche Kleidung kann Menschen mit Neurodermitis und empfindlicher Haut helfen? Technische Akademie Hohenstein, Bönnigheim, 3 November.

Wollina U, Abdel-Naser M B and Verma S (2006). 'Skin physiology and textiles—consideration of basic interaction', In *Biofunctional Textiles and the Skin*, Hipler U C and Elsner P (eds.), Volume 33 of Burg G (ed.) '*Current Problems in Dermatology*', Karger, Basel, pp. 1–16.

Zikeli S (2006). 'Production process of a new cellulosic fiber with antimicrobial properties', In *Biofunctional Textiles and the Skin*, Hipler U C and Elsner P (eds.), Volume 33 of Burg G (ed.) '*Current Problems in Dermatology*', Karger, Basel, pp. 110–126.

© Woodhead Publishing Limited, 2011

10

Mechanical skin irritations due to textiles

U. WOLLINA, Academic Teaching Hospital
Dresden-Friedrichstadt, Germany

Abstract: This chapter discusses the role of skin quality and function in the interaction with textiles, in particular clothing and bedding. The typical cutaneous reactions to mechanical stress are described. Recently developed techniques to measure possible irritating mechanical factors of fabrics and textiles are described in brief as well as contributing factors of fabrics and textiles to induce irritation on skin. The final part will discuss some clinical aspects of dermatoses related to mechanical irritation by fabrics and textiles.

Key words: fabrics, textiles, yarns, human skin, barrier function, skin glands, nerval function, friction hypermelanosis, decubitus, chronic venous insufficiency, atopic dermatitis.

10.1 Introduction

Textiles are among the environmental factors that come closest to the skin, the natural barrier of our body. Therefore textiles and fabrics often have been named the 'second skin'. This 'second skin' interacts in various ways with our own skin depending on both the qualities of textiles and fabrics and the quality of human skin. Other factors of importance in these interactions are humidity, temperatures and wind, allergens, pollutants and other chemicals, radiation and pre-existing skin disease (Wollina *et al*., 2006).

10.2 Human skin

The human skin is most important for barrier function of the whole body. The surface is about 1.8 m^2 with a weight of 10 kg. The epidermis is the outmost layer of skin. Its thickness varies by body region with the greatest thickness on palms and soles. The basal layer is composed of transient amplifying cells and differentiating basal cell of cuboidal shape. The spinal layer is composed of differentiating cells that become more and more flattened. The proliferative activity is lower than in the basal layer. The uppermost part of the spinal layer with prominent intracellular granules (keratohyalin granules and Odland bodies) is named granular layer. On top of this living layer there is the horny layer or stratum corneum (SC). This is a complex and dynamic structure of corneocytes, cells without a nucleus, lipid membranes and proteins that is responsible for human adaption to terrestrial life (Cartlidge, 2000).

© Woodhead Publishing Limited, 2011

The SC is composed like bricks and mortar, with bricks representing corneocytes and mortar for intercellular lipidis, composed of sphingolipids, cholesterol and free fatty acids. The SC remains metabolically active despite the loss of nuclei (Elias and Feingold, 2001; Proksch *et al*., 2008; Schmuth *et al*., 2008).

Corneocyte turnover and epidermal proliferation is controlled by desquamatory proteases and protease inhibitors in the epidermis. Disorders in barrier function and disruption of barrier homeostasis have been associated with changes in the expression patterns of epidermal serine proteases and variations in serine protease activity have also been identified at different body sites. The major route of permeation is around the corneocytes, therefore, the larger the corneocytes the longer the route for the permeation. Corneocyte size is dependent on the site on the body and this can be directly related to the permeability. Transepidermal water loss (TEWL) is a measure of the amount of water from within the skin to the external atmosphere. It was recently shown that variations in corneocyte size at different anatomical sites were reflected in TEWL at these sites. The path length at different body sites was calculated using a simple geometric equation and a direct reciprocal relationship between the path length and TEWL was identified. A linear trend between cell size and cell layers at different sites is also evident in the data. Since higher protease activity should result in smaller corneocyte sizes and fewer cell layers, this in turn may be related to reported variations in enzyme activity at these sites (Hadgraft and Lane, 2009).

In an *in vitro* mechanics approach to quantify the intercellular delamination energy and mechanical behaviour of isolated human SC in a direction perpendicular to the skin surface, effects of temperature, hydration, and a chloroform–methanol treatment to remove intercellular lipids were explored. The delamination energy for debonding of cells within the SC layer was found to be sensitive to the moisture content of the tissue and to the test temperature. Delamination energies for untreated stratum corneum were measured in the range of 1–8 J/m^2 depending on test temperature. Fully hydrated specimen energies decreased with increasing temperature, while specimens hydrated by room humidity exhibited more constant values of 2–4 J/m^2. Lipid-extracted specimens exhibited higher delamination energies of approximately 12 J/m^2, with values decreasing to approximately 4 J/m^2 with increasing test temperature. The peak separation stress decreased with increasing temperature and hydration, but lipid-extracted specimens exhibited higher peak stresses than untreated controls. The delaminated surfaces revealed an intercellular failure path with no evidence of tearing or fracture of cells. The highly anisotropic mechanical behaviour of the SC is related to the underlying SC structure (Wu *et al*., 2006).

Barrier function is influenced by temperature, skin hydration, skin site, age and skin diseases. With higher humidity, penetration of water soluble small substances increases. Occlusion can be caused by skin folds or textiles and gloves. It can remarkably increase penetration. Dry skin can cause breaks and desquamation

© Woodhead Publishing Limited, 2011

leading to the formation of fissures. This will deeply impair the barrier function (Taljebini *et al*., 1996; Hildebrandt *et al*., 1998).

Impairments of the epidermal barrier will also change the mechanical properties of human skin. A suction cup device commonly used for measurement of skin mechanics was used to provide a defined stress to the skin using the ventral forearm in 16 healthy volunteers. The integrity of the barrier function was assessed by TEWL and skin capacitance. Significant increases were established in trans epidermal water loss ($p < 0.01$) with concomitant significant decreases in capacitance ($p < 0.05$) following 400 mbar and 600 mbar of suction, suggesting that the mechanical integrity of the skin barrier was disrupted. A significant increase in distensibility ($p < 0.05$) and hysteresis ($p < 0.01$) was found following stripping, relating the role of the skin barrier to the overall mechanical properties of the skin. This study showed that the water permeability of the epidermis was significantly affected by the application of mechanical stress to the skin and vice versa, the mechanical properties of the skin were altered when the barrier was compromised. These observations suggest that the mechanical strength of the skin barrier may play a role in the development of, for example, friction dermatitis and other skin diseases affected by mechanical stress (Pedersen and Jemec, 2006).

Although the epidermis is the organ in direct and close contact to textiles, the underlying tissue layers, i.e. the dermis and subdermal adipose tissue are important for the biomechanics of skin. The *in vivo* mechanical behaviour of the upper skin layer (here defined as epidermis and papillar dermis) was characterised using a combined experimental and modelling approach. The work was based on the hypothesis that experiments with different length scales represent the mechanical behaviour of different skin layers. Suction measurements with aperture diameters of 1, 2 and 6 mm were combined with ultrasound and optical coherence tomography to study the deformation of the skin layers. The experiments were simulated for small displacements with a two-layered finite element model representing the upper layer and the reticular dermis. An identification method compared the experimental and numerical results to identify the material parameters of the model. For one subject the whole parameter estimation procedure was completed, leading to a stiffness of C (10, µl) = 0.11 kPa for the top-layer and C (10, rd) = 0.16 MPa for the reticular dermis. This unexpected, extreme stiffness ratio of the material parameters led to convergence problems of the finite element software for most of the individuals (Hendriks *et al*., 2006).

10.3 Skin irritation

Skin irritation or irritant contact dermatitis is an unspecific damage due to contact with either chemical substances or mechanical factors. Although any skin site might be affected, the hands are the most common affected area in professional life (Bauer *et al*., 2001).

© Woodhead Publishing Limited, 2011

10.4 Skin responses to mechanical forces

The skin is exceptionally resistant to mechanical forces. Depending on the nature and duration of the mechanical stress, the skin response can be quite variable. Mechanical factors influence the epidermal structure (thickness of stratum corneum and epidermis), consistency of dermis, local blood supply, pigmentation and innervation. The type of skin reaction depends on the frequency, intensity and direction of the exogenous force.

10.4.1 Hyperpigmentation

Protracted rubbing or pressure from clothing, belts, suspenders or prostheses may produce minimal skin thickening but pronounced hyperpigmentation, in which increased melanin production and incontinence of pigment both play a role. Such changes are far more common in overweight individuals, especially in intertriginous regions. A typical example is diffuse dark areas on the shoulders of heavy women secondary to the pressure from brassiere straps. Another cause for hyperpigmented skin is the development of localised cutaneous amyloidosis (Trattner and David, 2000).

10.4.2 Blisters

Everyone has had a blister following marked physical activity. Common scenarios include rowing a boat for the first time, a session of hoeing in the garden, or a long hike. Blisters can be disabling for soldiers or athletes, although they are generally only a nuisance. Patients with structural abnormalities at the epidermal–dermal junction, such as those with epidermolysis bullosa, tend to develop blisters when much smaller forces are applied. Some patients with mild variants of epidermolysis bullosa are first identified when forced to do heavy physical activity such as marching during initial military training.

10.4.3 Hyperkeratotic changes

Reactive changes of acanthosis and hyperkeratosis produce a thickened epidermis that is then better able to resist mechanical forces. The thickened stratum corneum usually has a yellow tint. The various types of hyperkeratotic change are dependent on the localisation and triggering factors.

Any repetitive rubbing force can induce a *callus*. The same activities that acutely cause blistering lead to calluses as a protective reaction. The nature of the pressure and the presence of minor anatomical variations determine the location and form of the callus. One need only to look at the hands of a competitive rower to see that symmetric calluses over the thenar and hypothenar eminences as well as the metacarpal heads and often the fingers provide the protection needed to withstand

© Woodhead Publishing Limited, 2011

the great mechanical stresses involved. Other typical calluses are those just proximal to a ring or over the heel or metatarsal head when shoes do not fit properly. Calluses on the tips of the toes may be a clue to a peripheral neuropathy (Abouaesha *et al*., 2001). Sometimes calluses are an occupational marker. In the past, one spoke often of milkmaid's callus appearing typically on the dorsal surface of the thumb, which was flexed during milking. Another interesting stigma is 'Yoga sign' – hyperkeratotic, often grey plaques over the outer ankle joints by sitting in a position with crossed legs. In the histopathology of such lesions there is both acanthosis and marked hyperkeratosis (Verma and Wollina, 2008). Another cause for callus development is a peripheral neuropathy, mainly the sensory neuropathy due to underlying diseases of the autonomous nerval system (Wollina *et al*., 2004).

Clavi (synonyms: corns, soft corns) typically develop in response to pressure combined with a sharp or discrete underlying abnormality. Corns are more common in women, because they tend to wear more tightly fitting shoes, which is the usual triggering factor. The key finding for distinguishing a corn from a callus is the central plug or core. A typical corn is 5–8 mm in diameter, yellow, often dome-shaped, and usually sensitive to pressure. The central core or eye is generally the most sensitive region. There may be surrounding erythema and sometimes fistulas develop. Secondary infections may occur in patients with predisposing problems such as diabetes mellitus. Soft or interdigital corns are usually less sharply bordered and have a white, macerated surface. They usually are found between the fourth and fifth toes, arising when the toes are squeezed too tightly together, such as in ballet dancers. Soft corns often reflect an underlying bony spur, so that radiological evaluation is appropriate. The epidermis is hyperkeratotic, acanthotic, and does not contain koilocytes, although the granular layer may be prominent. A clavus will show the central plug if sectioned properly, while a callus will not. In the dermis, there is often edema, necrosis, and fibrosis, which can extend to the underlying joint capsule. Clavi can be debrided just like calluses. Once the hyperkeratotic outer layer is removed, sometimes one can more accurately assess the underlying disorder. Pads, especially doughnut-shaped corn pads, are also popular. Annular pads may provide relief but can elevate the corn by causing pressure at its base. Operative approaches to corns and calluses are best left to podiatrists or orthopaedic surgeons who can most accurately assess whether an underlying bony defect requires correction. If fistulas develop, especially between the digits, surgery is often required. The surgical scars may serve as a nidus for renewed callus formation. The ideal solution is to purchase shoes that do not produce pressure and thus allow the problem to resolve slowly. Once again, podiatrists can provide the best guidance and also recommend appropriate insets and pads.

10.4.4 Black heel

Sharp mechanical pressure applied to normally hyperkeratotic regions may produce haemorrhage into the stratum corneum. Basketball players are perhaps

© Woodhead Publishing Limited, 2011

most prone, especially at the beginning of the playing season; but any activity associated with sudden stops and starts may be responsible. Dancers and individuals walking down mountains get similar lesions on their toes or beneath their toenails. Any mechanical pinching injury to the hands or feet may produce a similar change. Usually one can see linear or punctuate dark brown spots that represent haemorrhage in the stratum corneum. Subungual haemorrhage is the nail equivalent (Crissey and Peachey, 1961).

10.4.5 Decubitus ulcer (also known as pressure sore/bed sore)

A decubitus ulcer is the result of prolonged pressure that produces ischaemic necrosis of the skin and even soft tissue. The best known decubitus are those over the ischial tuberosities in bedridden patients who are unable to move. While everyone is aware of the importance of turning and moving patients who are paralysed or lack sensory input, often the sudden development of decubital ulcers in injured patients, especially those in casts, comes as a surprise. Children may develop ulcers under a cast in a matter of days. Patients in poor general condition are more likely to develop decubital ulcers, as are those individuals with peripheral vascular disease. The heels are another susceptible spot in such individuals. Continuous pressure causes an anaerobic metabolic state with accumulation of toxic products. Increased capillary permeability and vessel dilation leads to edema and inflammatory infiltrates. A paradoxic steal effect occurs, as the superficial tissues become hyperaemic while the deeper tissues are further deprived of adequate oxygen. Thus there is deep necrosis prior to the superficial damage which is the usual first clinical warning. Incontinence and infections are aggravating factors (Reddy *et al.*, 2008; Wollina, 2009).

A pressure-related deep tissue injury (DTI) is a severe pressure ulcer, which initiates in muscle tissue overlying a bony prominence (e.g. the ischial tuberosities) and progresses outwards through fat and skin, unnoticed by the paralysed patient. In a recent study the strain and stress peaks in the gluteus muscle and fat tissues under the ischial tuberosties of six healthy and six paraplegic patients have been compared, using the coupled magnetic resonance imaging finite-element (MRI-FE) method. Peak principal compression, principal tension, von Mises and shear strains in the gluteus were 1.2-, 3.1-, 1.4- and 1.4-fold higher in paraplegics than in healthy subjects, respectively ($p < 0.02$). Peak gluteal compression and shear stresses decreased by as much as 70% when the paraplegic patients moved from a sitting to a lying posture, indicating the effectiveness of recommending such patients to lie down after prolonged periods of sitting. The findings support the hypothesis that internal tissue loads are significantly higher in paraplegics, and that postural changes significantly affect these loads. The method of analysis is useful for quantifying the effectiveness of various interventions to alleviate

© Woodhead Publishing Limited, 2011

Table 10.1 Classification of pressure sores

Grade	Depth
I	Epidermis, dermis
II	Subcutaneous fat
III	Fascia, muscles
IV	Tendons, bone, joints
V	Undermining, pockets, fistulas

Source: Thomas (2001)

sub-dermal tissue loads at sites susceptible to pressure ulcers and DTI, including cushions, mattresses, recommendations for posture and postural changes, etc (Linder-Ganz *et al*., 2008).

Decubitus ulcers start as persistent, usually painless, livid oedematous lesions directly over a bony prominence. They are often overlooked until the pressure produces necrosis with either blisters or a sharply demarcated dry lesion. As the skin integrity is progressively destroyed, the wound no longer remains dry but usually becomes infected and undermined and involves deeper structures such as fat, fascia, tendons, muscles, and even bones. If the patient has intact sensation, the lesions are painful. The long-term persistence of decubital ulcers is one of the factors associated with amyloidosis. Decubital ulcers can be divided into five stages (Thomas, 2001; Table 10.1).

10.5 Measurement of irritating mechanical factors

Quantitative measurement of skin biomechanical properties has been used effectively in the investigation of physiological changes in tissue structure and function and to determine treatment efficacy. As the methods are applied to new questions, tissue characteristics that may influence the resultant biomechanical properties are important considerations in the research design. For certain applications, variables such as dermal thickness and subdermal tissue composition, as well as age and/or solar exposure, may influence the skin biomechanics. In a comparative trial the influence of dermal thickness, tissue composition, and age on the skin biomechanical properties at the shoulder, thigh, and calf was measured among 30 healthy females. Two devices were compared, i.e. the Biomechanical Tissue Characterisation System and the Cutometer SEM 575 Skin Elasticity Meter, to determine the effect of tissue sampling size. Dermal thickness was measured with 20 MHz ultrasound (Dermascan C) and tissue composition was inferred from anthropomorphic data. Skin thickness was significantly correlated with stiffness, energy absorption, and $U(r)/U(f)$ for the shoulder. Body mass index (BMI) was significantly correlated with stiffness (negative correlation), energy

© Woodhead Publishing Limited, 2011

absorption (positive), and skin thickness (negative) for the shoulder. Significant differences across body sites were observed. The calf was significantly different from the thigh and shoulders for all parameters ($p < 0.05$, one-way ANOVA). The calf had significantly lower laxity, laxity percentage, elastic deformation, energy absorption, elasticity, elasticity percentage, $U(r)$, $U(f)$, and $U(r)/U(f)$ and significantly higher stiffness compared with the thighs and shoulders. The thigh and shoulder sites were significantly different for all parameters except $U(r)/U(f)$, elasticity percentage, laxity percentage, and stiffness. The dominant and non-dominant sides were significantly different. The dominant side (right for 90% of the subjects) had increased stiffness and decreased energy absorption (tissue softness, compliance) compared with the left side. A significant ($p \leq 0.02$) negative relationship with age was seen for all biomechanical measures except stiffness at the shoulder. For the thigh and calf sites, significant negative correlations with age were found for elasticity percentage, $U(r)$, and $U(r)/U(f)$. Age and skin thickness were not correlated in this population. Skin thickness and age influenced the energy absorption at the shoulder site. The biological elasticity at the calf site could be predicted by age and BMI. The biological activity at the thigh site could be predicted by skin thickness and BMI. Significant regional variations in biomechanical properties and dominant side effects were observed. The biomechanical properties were significantly influenced by age. Certain properties varied with dermal thickness and tissue composition. The parameters were well correlated between the two instruments. The Cutometer, with its smaller aperture, was found to be more sensitive to age relationships (Smalls *et al*., 2006).

In another study a new method called indentation test to determine mechanical properties of human skin has been evaluated (Pailler-Mattei, 2004). The principle of the measurements consists in applying an *in vivo* compressive stress on the skin tissue of an individual's forearm. These measurements show an increase in the normal contact force as a function of the indentation depth. The interpretation of such results usually requires a long and tedious phenomenological study. The authors propose a new method to determine the mechanical parameters which control the response of skin tissue. This method is threefold: experimental, numerical, and comparative. It consists of combining experimental results with a numerical finite elements model in order to find out the required parameters. This process uses a scheme of extended Kalman filters. The first results presented in this study correspond to a simplified numerical modelling of the global system. The skin is assumed to be a semi-infinite layer with an isotropic linear elastic mechanical behaviour. This analysis will be extended to more realistic models in further works (Delalleau *et al*., 2006).

Recently, the friction coefficient have been used as the decision index of the progress for the bacterial aliments in the field of the skin physiology and the importance of friction coefficient have been increased in the skin care market because of the needs of the well-being times. In addition, the usage of friction coefficient is known to have the big discrimination ability in classification of human

© Woodhead Publishing Limited, 2011

constitutions, which is utilised in the alternative medicine. In a recent study, a system was designed which uses multi axes load cell and hemi-circular probe to measure the friction coefficient of hand skins repeatedly. Using this system, the relative repeatability error for the measurement of the friction coefficient was below four per cent The coefficient is not concerned in curvatures of tipps (Song *et al*., 2008).

The skin on the face is directly attached to the muscle through the superficial musculoaponeurotic system. This can be used to probe skin mechanical properties *in vivo* using digital image speckle correlation (DISC), which measures the intrinsic cutaneous pore structure displacement following a natural facial deformation. A series of images is taken, then analysed with DISC to create a displacement vector diagram, from which one can obtain spatially resolved information regarding facial deformation. The functional form of the displacement was investigated as a function of age, location on the face, and skin treatment. By this method it could be shown that facial skin displacement follows the direction of muscular movement and reflects the magnitude of the applied forces. Using DISC vector field analysis, it was noted that as the skin ages the distribution of forces becomes more condensed, with a marked spatial asymmetry. Analysis of the data in the perioral region, disclosed that the skin elasticity decreases exponentially with age, with a decay constant of approximately 32 years. Similar results, but with higher amplitude, were also found for the periorbital region. Finally, DISC vector field analysis also shows that the location of maximal stress correlated with the location of existing facial wrinkles. The DISC method, as a non-contact technique, is a potential clinical research tool for the diagnosis of facial skin conditions and underlying muscular activity. These factors can be used to monitor the effects of aging, formation of wrinkles, and the efficacy of treatment (Staloff *et al*., 2008).

The precise determination of skin's mechanical properties is still an open question. When performing an *in vivo* test, the piece of skin tested is not as well defined as it is in material testing. Moreover, the body zone and the body posture imply an initial stress on the skin. Consequently, a precise mechanical analysis needs a precise measurement of the natural skin tension. A new method that is based on an extensiometry test with the combined use of traction and compression has been developed. The tested skin sample is well defined and protected from surrounding effects by follower tabs. The size and shape of the device have been optimised by a finite element modellisation. The method was tested with elastomers pre-tensioned at different loads. It is shown that the initial tension can be retrieved with good precision. Tests were then performed *in vivo* on the forearm for different arm positions. It is shown that initial tension could be only clearly determined for the highest skin tension, although the skin presented very different traction behaviour with different arm positions (Jacquet *et al*., 2008).

A specific bio-tribometer has been developed to study the physical properties of the skin *in vivo* by measuring the maximum adhesion force between the skin and the bio-tribometer. The lipidic film present on skin surface is responsible for skin adhesion due to capillary phenomena. The measure of pull-off force between skin

© Woodhead Publishing Limited, 2011

and bio-tribometer estimates the liquid/vapour surface tension of the lipidic film (gamma(LV) approximately 6.3 mJ/m^2 in 30-year-old volunteer). The kinetic of sorption/desorption (sorption means indifferently adsorption and absorption process) of distilled water from the skin has been observed through the variation of the indenter/skin pull-off force versus time after distilled water application to the skin surface. This permits to follow in real time the variation of the skin physicochemical properties after liquid application onto the skin surface. Finally, the increase of skin friction coefficient after distilled water application onto skin surface was explained by the capillary adhesion force between the probe and the skin (Pailler-Mattei *et al*., 2009).

An analytical mathematical model for friction between a fabric strip and the volar forearm has been developed and validated experimentally. The model generalises the common assumption of a cylindrical arm to any convex prism, and makes predictions for pressure and tension based on Amontons' law. This includes a relationship between the coefficient of static friction (μ) and forces on either end of a fabric strip in contact with part of the surface of the arm and perpendicular to its axis. Coefficients of friction were determined from experiments between arm phantoms of circular and elliptical cross-section (made from plaster of Paris covered in neoprene) and a nonwoven fabric. As predicted by the model, all values of μ calculated from experimental results agreed within ± 8%, and showed very little systematic variation with the dead weight, geometry, or arc of contact used. With an appropriate choice of coordinates the relationship predicted by this model for forces on either end of a fabric strip reduces to the prediction from the common model for circular arms. This helps to explain the surprisingly accurate values of μ obtained by applying the cylindrical model to experimental data on real arms (Cottenden *et al*., 2008a).

The method was used to measure the coefficient of static friction for three different nonwoven materials on the normal (dry) and over-hydrated volar forearms of five female volunteers (ages 18–44 years). The method proved simple to run and had good repeatability: the coefficient of variation (standard deviation expressed as a percentage of the mean) for triplets of repeat measurements was usually (80% of the time) less than 10%. Measurements involving the geometrically simpler configuration of pulling a weighted fabric sample horizontally across a quasi-planar area of volar forearm skin proved experimentally more difficult and had poorer repeatability. However, correlations between values of coefficient of static friction derived using the two methods were good ($R = 0.81$ for normal (dry) skin, and 0.91 for over-hydrated skin). Measurements of the coefficient of static friction for the three nonwovens for normal (dry) and for over-hydrated skin varied in the ranges of about 0.3–0.5 and 0.9–1.3, respectively. In agreement with Amontons' law, coefficients of friction were invariant with normal pressure over the entire experimental range (0.1–8.2 kPa) (Cottenden *et al*., 2008b).

The 'behind-the-knee' method (BTK test), using the popliteal fossa as a test site, evaluates both the inherent chemical irritation, and the potential for mechanical

© Woodhead Publishing Limited, 2011

irritation of substrates and products. This approach eliminates some of the difficulties of in-use clinical test systems while still providing reliable results. In in-use clinical tests, volunteer panellists were provided with catamenial products to use in place of their normal product. In the BTK test, samples were applied daily to the popliteal fossa using an elastic athletic band. In both studies, irritation reactions were scored visually. Levels of irritation in the BTK test are consistently higher than those of standard patch tests, illustrating the contribution of mechanical irritation to the overall irritant potential of materials and products. Repeated tests on identical test materials demonstrated that the BTK test results are reproducible. Side-by-side comparisons of the BTK test and in-use clinical tests demonstrated that the BTK test produces results of similar quality to the in-use clinical. By using several concurrent panels with a common test material, it is possible to compare the irritant properties of several materials at once. The test method has proven reliable and versatile in testing a wide variety of materials, including menstrual pads, topsheets, interlabial pads, panty liners, tampons and lotion coatings on products. Unlike in-use clinicals, the BTK test allows the direct comparison of two products at one time on the same individual, and is easily adapted to investigative programmes. It is subject to fewer confounding factors, is much easier to implement, has a shorter turnaround time, and is less expensive than in-use clinical testing. Importantly, unlike standard patch tests, the BTK test evaluates both the inherent chemical irritation associated with materials and the mechanical irritation owing to friction. Although the BTK test was developed using catamenial products, the test system provides a valuable alternative for evaluating any material where mechanical irritation may play a role, including textiles (Farage, 2006).

10.6 Factors causing a textile to be mechanically irritating

Human skin is permanently exposed to friction and shear forces of fabrics of clothes, bedding and other textile applications. In healthy normal skin a lubricating surface coating derived from the activity of sweat and sebaceous glands decreases friction. Since the anatomical distribution of these skin glands varies considerably, the protective effect of skin surface coating is not uniform on all body sites. The lipid and water content of SC will also influence the tolerability of friction and shear forces.

A textile consists of various components. These include fibres with various diameters, surface structures and other morphologies, surface coatings and flexibility. The fibres are used to produce yarns, like spun yarns, smooth yarns and textured filament yarns. The yarns may be twisted together to form twisted yarns. Fabrics are categorised into woven fabrics, knit fabrics, nonwoven and felted fabrics. The fabrics need a final finishing, colouring and coating (Sewerev, 2003). Laundering brings textiles in contact to detergents that often are claimed to be responsible for irritant dermatitis due to textiles. Scientific investigations, however, have shown that there is little evidence for health risks by laundering (Rodriguez *et al*., 1994; Matthies, 2003).

© Woodhead Publishing Limited, 2011

Textiles, in particular clothing, interact with skin functions in a dynamic pattern. Microclimate in the skin/clothing system and especially the skin responses relates to the moisture and heat transfer within this system and plays a critical role in skin irritation from textiles. When fluid transport from the skin into a textile structure is higher than the fluid transport from deeper layers into the epidermis this will cause dryness and eventually roughness. Mechanical properties like roughness of fabric surface are responsible for non-specific skin reactions like wool intolerance or keratosis follicularis (colour Plate I, between pages 262 and 263) (Wollina *et al*., 2006).

Changes in knit structure and density have an impact on the mechanical and hand properties of fabrics that has been evaluated for weft-knitted fabrics for outerwear. Tensile properties, bending and shear properties increase for fabrics with a higher density. Compression values decrease somewhat as knit density increases. Surface properties such as softness and smoothness increase with density. Smoothness decreases in contrast to softness with increased knit density (Choi, 2000). The effect on acceptance might be even higher for underwear clothes.

Stitches, nods and use of different materials within a garment may influence the mechanical effects on skin, in particular friction and shear forces (Plate II and Plate III). Glabarous and hairy skin behave differently, with both the fibre type of fabrics and moisture determining fabric-to-skin friction (Kenins, 1994).

Friction can be sub-divided into static and dynamic friction. *Static friction* is the force required to break away from a stick condition. *Dynamic friction* is the force needed to maintain relative motion. According to the hairiness of natural yarns they tend to have higher coefficients of friction (COF) (Jeddi *et al*., 2003; Zurek *et al*., 1985; Wilson, 1963).

The influence of skin friction on the perception of fabric texture and pleasantness has been evaluated in eight males. They were exposed to various environmental conditions: neutral (comfortable), hot–dry, hot–humid, and eventually return to neutral. During each condition that lasted 20 minutes, six different fabrics were slowly pulled across the subject's forearm. The friction force correlated with skin wettedness. As force and skin wettedness increased all subjects rated the fabrics more textured (rougher) and less pleasant (Gwosdow, 1986).

10.6.1 Towels

In Asia, macular amyloidosis caused by prolonged friction from a rough nylon towel or brush is common, and macular amyloidosis and lichen amyloidosis occasionally occur together, as so-called biphasic amyloidosis. One can find mostly unique symmetrical papular lesions on the upper back and shoulders. Lesions comprised slightly shiny, brownish, fine uniform papules approximately 0.5 mm in diameter, showing a partially linear, annular or rippled arrangement (Wong and Lin, 1988; Yoshida *et al*., 2009). Only a few reports come from Europe

© Woodhead Publishing Limited, 2011

(Siragusa *et al*., 2001). There is an analogous friction dermatosis on the hip commonly seen in India and neighbouring countries where women wear a sari (Wollina *et al*., 2006) (Plate IV).

10.6.2 Socks

Socks are a special textile that interacts with both the foot and footwear. Therefore socks can play a critical role in prevention of blisters, pressure sores and infection in diabetics and other persons with an impaired neurosensory function (Plate II and Plate III) (Heide *et al*., 2006).

In a recent study a three-dimensional finite element model for simulating the foot-sock-insole contact was developed to investigate the biomechanical effects of wearing socks with different combinations of frictional properties on the plantar foot contact. The dynamic plantar pressure and shear stress during the stance phases of gait were studied through finite element computations. Three cases were simulated, a barefoot with a high frictional coefficient against the insole (0.54) and two socks, one with a high frictional coefficient against the skin (0.54) and a low frictional coefficient against the insole (0.04) and another with an opposite frictional properties assignment. Wearing a sock of low friction against the insole to allow more relative sliding between the plantar foot and footwear was found to reduce the shear force significantly: at the rear foot from 3.1 to 0.88 N, and at the forefoot from 10.61 to 1.61 N. The shear force can be further reduced to 0.43 N at the rear foot, and 1.18 N at the forefoot, when wearing the sock with low friction against the foot skin and high friction set against the insole. Wearing sock with low friction against the foot skin was found to be more effective in reducing plantar shear force on the skin than the sock with low friction against the insole. The risk of barefoot walking in developing plantar shear related blisters and ulcers might be reduced by socks wearing especially those with low friction against the foot skin (Dai *et al*., 2006).

10.6.3 Compression stockings and bandages

Compression bandages or stocking are a hallmark of the conservative treatment of chronic venous insufficiency. The major goal is to get a good working pressure without decrease of time of wearing, usually during the day. Pressure gained by these devices has been measured in various clinical studies. Compression stockings with higher pressure levels applied higher skin pressure on the lower limb. The pressure at the anterior side was far higher than that in the medial and lateral directions. The distribution patterns of skin pressure at transverse sections were similar to the anatomic outlines of cross sections of the leg (Liu *et al*., 2005).

The stockings/bandages can deteriorate dry skin and this increases the shear forces of those textiles on the skin surface. Compression stockings with an integrated skin care system were evaluated in 42 chronic venous insufficiency patients (Stage I and II according to Widmer) in prospective, randomised

© Woodhead Publishing Limited, 2011

explorative trial. Patients were randomised to either elastic compression stockings (VenoTrain micro; Bauerfeind) or the same stockings with an integrated skin care system (VenoTrain micro balance). Investigations on skin quality were performed before and seven days after daily usage of the stockings. Measurements included corneometry, TEWL and non-contact optical topimetric evaluation of skin surface (FOITS Dermatop) for roughness. All parameters were in favour of stockings of the micro-balance type. Therefore intensified skin care for compression therapy will increase compliance and patient's comfort (Jünger, 2008).

Another option is the use of moisturisers before wearing compression stockings. The interaction of topical skin care products such as moisturising creams has to be considered for the durability of medical compression stockings and bandages (Wollina *et al*., 2003; Van Gest *et al*., 2003).

10.6.4 Bedding

The role textiles play in the formation and prevention of pressure ulcers needs more study. The fact remains that textiles, such as clothing and bedding, have a considerable influence on factors, such as pressure, shear/friction, and skin hydration, which contribute to skin ulceration.

Immobility of residents was determined to be a significant factor of causing skin lesions and pressure ulcers. Immobility of residents contributes to a prolonged interaction between skin and fabrics and might increase the chances of skin lesions or bedsores (Zhong *et al*., 2008).

A study was performed to evaluate the contact phenomena at the skin–textile interface and the development of a purpose-built textile friction analyser (TFA) for the tribological assessment of skin–fabric interactions, in connection with decubitus prevention. Interface pressure distributions were recorded in the pelvic and femoral regions between supine persons and a foam mattress. Fabrics made of various natural and synthetic yarns were investigated using the TFA. A vertical load of 7.7 kPa was applied to the swatches, simulating high interface pressures at the skin–fabric interface and clinical conditions of bedridden persons. Fabrics were rubbed in reciprocating motions against a validated skin-simulating material to determine static as well as dynamic skin moisture and friction coefficients (COFs). Maximum contact pressures ranged from 5.2 to 7.7 kPa (39–58 mmHg) and exceeded the capillary closure pressure (32 mmHg) in all investigated bedding positions. For both COFs, a factor of 2.5 was found between the samples with the lowest and highest values. Our results were in a similar range to COFs found in measurements on human skin *in vivo*. The results showed that the test method can detect differences of 0.01 in friction coefficients (Gerhardt *et al*., 2008a).

The friction between the inner forearm and a hospital fabric was measured in the natural skin condition and in different hydration states using a force plate. Eleven males and eleven females rubbed their forearm against the textile on the force plate using defined normal loads and friction movements. Skin hydration

© Woodhead Publishing Limited, 2011

and viscoelasticity were assessed by corneometry and the suction chamber method, respectively. In each individual, a highly positive linear correlation was found between skin moisture and COF. No correlation was observed between moisture and elasticity, as well as between elasticity and friction. Skin viscoelasticity was comparable for women and men. The friction of female skin showed significantly higher moisture sensitivity. COFs increased typically by 43% (women) and 26% (men) when skin hydration varied between very dry and normally moist skin. The COFs between skin and completely wet fabric were more than two-fold higher than the values for natural skin rubbed on a dry textile surface. Increasing skin hydration seems to cause gender-specific changes in the mechanical properties and/or surface topography of human skin, leading to skin softening and increased real contact area and adhesion (Gerhardt *et al*., 2008b; Derler *et al*., 2007).

10.6.5 Textiles for atopic and sensitive skin

Atopic dermatitis (AD) is a chronic relapsing inflammatory skin disease which usually starts during the first years of life. It is the most severe manifestation of sensitive skin (SS). In the management of AD/SS, the best approach would require a combination of treatment, elimination of trigger factors, and improvement of the alterated of the skin barrier (Elias *et al*., 2008).

Garments are in direct contact with the skin all day long, and for this reason it is important to carefully choose suitable fabrics in atopic subjects who have disrupted skin. Wool fibres are frequently used in human clothes but are irritating in direct contact with the skin. Wool fibre has frequently been shown to be irritating to the skin of atopic patients/SS. Cotton is the most commonly used textile for patients with AD/SS; it has wide acceptability as clothing material because of its natural abundance and inherent properties like good folding endurance, better conduction of heat, easy dyeability and excellent moisture absorption. On the other hand, cotton contains short fibres which expand and contract, causing a rubbing movement that may irritate AD/SS (Mason, 2008). Silk fabrics help to maintain the body temperature by reducing the excessive sweating and moisture loss that can worsen xerosis. However, the type of silk fabric generally used for clothes is not particularly useful in the care and dressing of children with AD since it reduces transpiration and may cause discomfort when in direct contact with the skin. A new type of silk fabric made of transpiring and slightly elastic woven silk where sericin protein of silk has been removed is now commercially available (Microair Dermasilk) and may be used for the skincare of children with AD (Ricci *et al*., 2006).

In a clinical study preference of subjects with AD and normal skin for 100% fabrics for clothing and bedding versus cellulosic fibre Lyocell has been evaluated. Thirty subjects were enrolled and randomly selected to use cotton or Lyocell shirts, pyjamas, and bedding for one week. Following a one week wash-out period, participants wore the other fabric for another week. Overall, there was a

© Woodhead Publishing Limited, 2011

significant preference for Lyocell for its softness, temperature control, moisture control, and wrinkle resistance (Love and Nedorost, 2009).

On the other hand, the tolerability of fabrics is much less dependent on fibres used as long as the surface of the textile is smooth (Wollina *et al*., 2006) (Plate V). Bedding based on kapock fibres has been found to improve sleep in AD/SS individuals (Wollina *et al*., 1999). This is more due to thermoregulatory effects and moisture balance of the kapock fibre. However, the indirect effect is also a mechanical one that decreases the prickling sensation of the bedding on atopic skin.

The effects of softened fabrics on the skin were evaluated by a forearm wet and dry test, under conditions simulating real-life skin contact with fabrics. Fifteen volunteers with sensitive skin according to dermatological assessment and their own recognition entered a double-blind 12 day (three sessions per day) forearm wetting and drying test, using cotton fabrics washed with a powder detergent and softened or not with a liquid fabric conditioner. To simulate conditions of skin damage, a dilute solution of sodium lauryl sulfate was applied under patch to the forearm before the start of the study. Skin effects were evaluated by visual grading (redness, dryness and smoothness), by non-invasive skin stripping and measuring of Chroma *C** (squamometry), and by instrumental measurements (capacitance, transepidermal water loss, and colorimetry). Both the unsoftened and softened fabrics induced no deleterious effects on control or previously irritated skin. Furthermore, a mild beneficial effect was observed with the softened fabrics, particularly on previously irritated skin. The study findings suggest that softened fabrics may exert a reduced frictional effect on the skin (Piérard *et al*., 1994).

Twenty atopic volunteers entered a single-blind 12-day (three sessions per day) forearm wetting and drying test. Cotton fabrics were machine washed and liquid fabric conditioner was added or not to the final rinse. To simulate conditions of skin damage, a dilute solution of sodium lauryl sulfate was applied under occlusion to the forearm of each volunteer before the start of the study. Skin effects were evaluated by visual grading (redness, dryness and smoothness), squamometry and *in vivo* instrumental measurements (capacitance, transepidermal water loss and colorimetry). Rubbing of atopic skin with fabrics generally resulted in discrete to moderate alterations of the structure of the stratum corneum. Both for control and pre-irritated skin, all measured parameters indicated that softened fabric was less aggressive to the skin than unsoftened fabric. In the case of pre-irritated skin, the recovery of the skin was significantly faster when rubbed with softened than with unsoftened fabrics. In conclusion, softened fabrics help mitigate the skin condition in atopic patients (Hermanns *et al*., 2001).

10.7 References

Abouaesha F, van Schie CH, Armstron DG and Boulton AJ (2001). Plantar tissue thickness predicts high peak plantar pressure in the diabetic foot. *J Am Podiatr Med Assoc*, 94, 39–42.

© Woodhead Publishing Limited, 2011

Bauer A, Kelterer D, Stadeler M, Schneider W, Kleesz P, *et al*. (2001). The prevention of occupational hand dermatitis in bakers, confectioners and employees in the catering trades. Preliminary results of a skin prevention program. *Contact Dermatitis*, 44, 85–88.

Cartlidge P (2000). The epidermal barrier. *Semin Neonatol*, 5, 273–280.

Choi M-S (2000). Effect of changes in knit structure and density on the mechanical and hand properties of weft-knitted fabrics for outerwear. *Text Res J*, 70, 1033–1045.

Cottenden AM, Cottenden DJ, Karavokiros S and Wong WK (2008a). Development and experimental validation of a mathematical model for friction between fabrics and a volar forearm phantom. *Proc Inst Mech Eng* [H], 222, 1097–1106.

Cottenden AM, Wong WK, Cottenden DJ and Farbrot A (2008b). Development and validation of a new method for measuring friction between skin and nonwoven materials. *Proc Inst Mech Eng* [H], 222, 791–803.

Crissey JT and Peachey JC (1961). Calcaneal petechiae. *Arch Dermatol*, 83, 501.

Dai XQ, Li Y, Zhang M and Cheung JT (2006). Effect of sock on biomechanical responses of foot during walking. *Clin Biomech* (Bristol, Avon), 21, 314–321.

Day RD, Reyzelman AM and Harkless LB (1996). Evaluation and management of the interdigital corn: a literature review. *Clin Podiatr Med Surg*, 13, 201–206.

Delalleau A, Josse G, Lagarde JM, Zahouani H and Bergheau JM (2006). Characterization of the mechanical properties of skin by inverse analysis combined with the indentation test. *J Biomech*, 39, 1603–1610.

Derler S, Schrade U, Gerhardt L-C (2007). Tribology of human skin and mechanical skin equivalents in contact with textiles. *Wear*, 262, 1112–1116.

Elias PM and Feingold KR (2001). Coordinate regulation of epidermal differentiation and barrier homeostais. *Skin Pharmacol Appl Skin Physiol*, 2001, 14(Suppl 1), 28–34.

Elias PM, Hatano Y and Williams ML (2008). Basis for the barrier abnormality in atopic dermatitis: outside-inside-outside pathogenic mechanisms. *J Allergy Clin Immunol*, 121, 1337–1343.

Farage MA (2006). The behind-the-knee test: an efficient model for evaluating mechanical and chemical irritation. *Skin Res Technol*, 12, 73–82.

Gerhardt LC, Mattle N, Schrade GU, Spencer ND and Derler S (2008a). Study of skin–fabric interactions of relevance to decubitus: friction and contact-pressure measurements. *Skin Res Technol*, 14, 77–88.

Gerhardt LC, Strässle V, Lenz A, Spencer ND and Derler S (2008b). Influence of epidermal hydration on the friction of human skin against textiles. *J R Soc Interface*, 5, 1317–1328.

Gwosdow AR (1986). Skin friction and fabric sensations in neutral and warm environments. *Text Res J*, 56, 574–580.

Hadgraft J and Lane ME (2009). Transepidermal water loss and skin site: a hypothesis. *Int J Pharm*, 373, 1–3.

Heide M, Möhring U, Hänsel R, Stoll M, Wollina U and Heinig B (2006). Antimicrobial-finished textile three-dimensional structures. *Curr Probl Dermatol*, 33, 179–199.

Hendriks FM, Brokken D, Oomens CW, Bader DL and Baaijens FP (2006). The relative contributions of different skin layers to the mechanical behavior of human skin in vivo using suction experiments. *Med Eng Phys*, 28, 259–266.

Hermanns J-F, Goffin V, Arrese JE, Rodriguez C and Piérard GE (2001). Beneficial effects of softened fabrics on atopic skin. *Dermatology*, 202, 167–170.

Hildebrandt D, Ziegler K and Wollina U (1998). Electrical impedance and transepidermal water loss of healthy human skin under different conditions. *Skin Res Technol*, 4, 130–134.

© Woodhead Publishing Limited, 2011

Jacquet E, Josse G, Khatyr F and Garcin C (2008). A new experimental method for measuring skin's natural tension. *Skin Res Technol*, 14, 1–7.

Jeddi AAA, Shams S, Nosraty H and Sarsharzadeh A (2003). Relation between fabric structure and friction, Part I: woven fabrics. *J Text Inst*, 94, 223–234.

Jünger M (2005). Einfluss von Kompressionsstrümpfen auf die Barrierefunktion der Haut bei Patienten mit chronischer venöser Insuffizienz, integrierter klinischer und statistischer Auswertungsbericht, Universitäts-Hautklinik Greifswald, 08/2005. Available: www.bauerfeind.com

Kenins P (1994). Influence of fiber type and moisture on measured fabric-to-skin friction. *Text Res J*, 64; 722–728.

Linder-Ganz E, Shabshin N, Itzchak Y, Yizhar Z, Siev-Ner I and Gefen A (2008). Strains and stresses in sub-dermal tissues of the buttocks are greater in paraplegics than in healthy during sitting. *J Biomech*, 41, 567–580.

Liu R, Kwok YL, Li Y, Lao TT, Zhang X and Dai XQ (2005). Objective evaluation of skin pressure distribution of graduated elastic compression stockings. *Dermatol Surg*, 31, 615–624.

Love WE and Nedorost ST (2009). Fabric preferences of atopic dermatitis patients. *Dermatitis*, 20, 29–33.

Masson R (2008). Fabrics for atopic dermatitis. *J Fam Health Care*, 18, 63–65.

Matthies W (2003). Irritant dermatitis to detergents in textiles. *Curr Probl Dermatol*, 31, 123–138.

Pailler-Mattei C (2004). Caractérisation mécanique et tribologique de la peau humaine in vivo. Ph.D. Thesis, ECL-no. 2004–31.

Pailler-Mattei C, Nicoli S, Pirot F, Vargiolu R and Zahouani H (2009). A new approach to describe the skin surface physical properties in vivo. *Colloids Surf B Biointerfaces*, 68, 200–206.

Pedersen L and Jemec GB (2006). Mechanical properties and barrier function of healthy human skin. *Acta Derm Venereol*, 86, 308–311.

Piérard GE, Arrese JE, Rodríguez C and Daskaleros PA (1994). Effects of softened and unsoftened fabrics on sensitive skin. *Contact Dermatitis*, 30, 286–291.

Proksch E, Brandner JM and Jensen JM (2008). The skin: an indispensable barrier. *Exp Dermatol*, 17, 1063–1072.

Reddy M, Gill SS, Kalkar SR, Wu W, Anderson PJ and Rochon PA (2008). Treatment of pressure ulcers: a systematic review. *JAMA*, 300, 2647–2662.

Ricci G, Patrizi A, Bellini F and Medri M (2006). Use of textiles in atopic dermatitis: care of atopic dermatitis. *Curr Probl Dermatol*, 33, 127–143.

Rodriguez C, Calvin G, Lally C and LaChapelle JM (1994). Skin effects associated with wearing fabrics washed with commercial laundry detergents. *J Toxicol Cutan Ocular Toxicol*, 13, 39–45.

Schmuth M, Jiang YJ, Dubrac S, Elias PM and Feingold KR (2008). Thematic review series: skin lipids. Peroxisome proliferator-activated receptors and liver X receptors in epidermal biology. *J Lipid Res*, 49, 499–509.

Siragusa M, Ferri R, Cavallari V and Schepis C (2001). Friction melanosis, friction amyloidosis, macular amyloidosis, towel melanosis: many names for the same clinical entity. *Eur J Dermatol*, 11, 545–548.

Smalls LK, Randall Wickett R and Visscher MO (2006). Effect of dermal thickness, tissue composition, and body site on skin biomechanical properties. *Skin Res Technol*, 12, 43–49.

© Woodhead Publishing Limited, 2011

Song HW, Park YK, Lee SJ, Woo SY, Kim SH and Kim DR (2008). The development of the friction coefficient inspection equipment for skin using a load cell. *Conf Proc IEEE Eng Med Biol Soc*, 2008, 1545–1548.

Staloff IA, Guan E, Katz S, Rafailovitch M, Sokolov A and Sokolov S (2008). An in vivo study of the mechanical properties of facial skin and influence of aging using digital image speckle correlation. *Skin Res Technol*, 14, 127–134.

Swerev M (2003). What dermatologists should know about textiles. *Curr Probl Dermatol*, 31, 1–23.

Taljebini M, Warren R, Mao-Oiang M, Lane E, Elias PM and Feingold KR (1996). Cutaneous permeability barrier repair following various types of insults: kinetics and effects of occlusion. *Skin Pharmacol*, 9, 111–119.

Thomas DR (2001). Prevention and treatment of pressure ulcers: what works? What doesn't? *Cleve Clin J Med*, 68, 704–797.

Trattner A and David M (2000). Textile contact dermatitis presenting as lichen amyloidosus. *Contact Dermatitis*, 42, 107–108.

Van Gest AJ, Franken CPM and Neumann HAM (2003). Medical elastic compression stockings in the treatment of venous insufficiency. *Curr Probl Dermatol*, 31, 98–107.

Verma SB and Wollina U (2008). Callosities of cross legged sitting: 'Yoga sign' – an under recognized cultural cutaneous presentation. *Int J Dermatol*, 47, 1212–1214.

Wilson D (1963). A study of fabric-on-fabric dynamic friction. *J Text Inst*, 54, T143–T155.

Wollina U (2009). Disorders caused by physical and chemical damage. In Burgdorf WHC, Plewig G, Wolff HH and Landthaler M, Braun-Falco's, *Dermatology*, 3rd Edition. Springer, Heidelberg, New York, pp. 598–616.

Wollina U, Wilmer A and Karamfilov T (1999). Einsatzmöglichkeiten von Kawoll. *Melliand Textilberichte – Int Textile Rep*, 80, 197.

Wollina U, Heide M Müller-Litz W, Obenauf D and Ash J (2003). Functional textiles in prevention of chronic wounds, wound healing and tissue engineering. *Curr Probl Dermatol*, 31; 82–97.

Wollina U, Krönert C and Heinig B (2004). Bilateral callosities, plantar ulcers and peripheral neuropathy in a 15-year old nondiabetic boy – think of neuroborreliosis. *J Eur Acad Dermatol Venereol*, 19, 259–260.

Wollina U, Abdel-Naser MB and Verma S (2006). Skin physiology and textiles – consideration of basic interactions. *Curr Probl Dermatol*, 33, 1–16.

Wong CK and Lin CS (1988). Friction amyloidosis. *Int J Dermatol*, 27, 302–307.

Wu KS, van Osdol WW and Dauskardt RH (2006). Mechanical properties of human stratum corneum: effects of temperature, hydration, and chemical treatment. *Biomaterials*, 27, 785–795.

Yoshida A, Takahashi K, Tagami H and Akasaka T (2009). Lichen amyloidosis induced on the upper back by long-term friction with a nylon towel. *J Dermatol*, 36, 56–59.

Zhong W, Ahmad A, Xing MM, Yamada P and Hamel C (2008). Impact of textiles on formation and prevention of skin lesions and bedsores. *Cutan Ocul Toxicol*, 27, 21–28.

Zurek W, Jankowiak D and Frydrych I (1985). Surface frictional resistance of fabrics woven from filament yarns. *Text Res J*, 55, 113–121.

© Woodhead Publishing Limited, 2011

Plate I Keratosis follicularis in an atopic person. A typical presentation of atopic skin during winter, when humidity decreases and friction by clothing becomes visible.

Plate II Plantar callus.

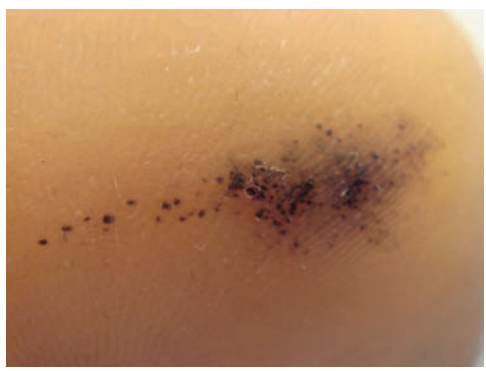


Plate III Black heel. Intracorneal bleeding due to shear forces by socks and shoes.

© Woodhead Publishing Limited, 2011

Plate IV Frictional hypermelanosis on the hip due to traditional clothing (sari).

(a) (b)

Plate V The effect of textile roughness on atopic skin (a) 'dirty neck' appearance due to clothing; (b) lichenoid dermatitis of the neck due to polyester-based clothing in a hot climate.

© Woodhead Publishing Limited, 2011

11

Allergies caused by textiles

R. WECKMANN, Dr. Rainer Weckmann
Textile Consulting, Germany

Abstract: This chapter summarises what is known about the subject 'Allergies caused by textiles', with the aim of avoiding such textiles especially in the field of medical textiles. As all known allergies caused by textiles are type 4, it is important that they are identified and the use of allergy-causing textiles is avoided. A number of defined substances and substance groups, used in the production of textiles, are known to cause allergies. Most of them are banned by the criteria of reliable Eco- or Consumer Safety Labels or by governmental restriction. It has therefore become possible to avoid these substances in the production of medical textiles.

Key words: types of allergy, allergies caused by textiles, nickel allergy, allergenic disperse dyes, formaldehyde allergy, silk glue allergy, latex allergy, medical textiles.

11.1 Introduction

This chapter covers different aspects of the subject 'allergies caused by textiles'. First, different types of allergies occurring in the field of medicine are examined. Put simply, only contact allergies are considered clinically significant. Following on from medical considerations, different allergenic substances in textiles, mostly dyes, are discussed. Knowledge concerning potential allergens in textiles allows a proper analysis of such substances. The risk of getting an allergy from textiles is also assessed. Since allergenic substances in textiles are well known it is possible to minimise or to fully eliminate them in textile production; textiles free of allergenic substances can then be identified either by an eco-label or by a consumer safety label. Following this, an overview of medical textiles is provided.

In the future the number of cases of allergies caused by textiles is expected to decrease further. One major reason for this is the increase in ecological awareness among textile consumers, textile producers and textile dealers. At the end of the chapter sources of further information are given, most of which are internet references to ensure that the information is current and up to date.

11.2 Types of allergies

In medical science various types of allergies exist. The classification of these is dependent on the way in which the allergens are taken into the body:

- *Inhalation allergy* is caused by breathing in of allergens, e.g. house dust or pollen.

© Woodhead Publishing Limited, 2011

- *Food allergy* can occur due to eating allergenic food such as nuts, strawberries, cow milk, chicken eggs, soy, etc.
- *Contact allergy* results from skin contact with an allergen such as nickel, dispersion dyes or ingredients in cosmetics.
- *Pharmaceutical allergy* can occur after the ingestion of pharmaceuticals, as in the well known example of penicillin allergy.
- *Insecticide allergy* can be caused by the sting of a honey bee, a wasp or a hornet.

A more medically scientific differentiation of allergy types is based on the immunological reaction of the allergen:

- *Type I*: *immediate-type allergy*. The most frequently occurring allergies, about 80–90% of all cases, belong to type I. Typical representatives of this allergy type are pollen allergy, house dust allergy, food allergy or hymenoptera venom allergy.
- *Type II*: *cytotoxic reaction*. Type II allergies occur only rarely. Examples for this allergy type are autoimmune diseases or the destruction of the red blood corpuscles after a blood transfusion with an incongruous blood group.
- *Type III*: *immune complex formation*. Representatives of this type of allergy are the so-called pigeon breeder's lung or farmer's lung.
- *Type IV*: *cellular immune reaction*. This a delayed-type allergy, e.g. nickel allergy, disperse dyes allergy and other contact allergies.

The allergy types I, II and III are mediated by the humoral immune response (i.e. by secreted antibodies). The type IV allergy is cell-mediated via T-cells. Type IV allergies predominantly trigger symptoms on the skin. All known allergies which are caused by textiles belong to type IV.

11.3 Main types of allergies caused by textiles

It is frequently claimed that textiles are to blame for allergies experienced by the wearer. In some cases the media exaggerate; in other cases consumers wrongly attribute non-allergic reactions of the skin to an allergy to textiles. But what is the truth?

Non-allergic skin irritations are caused by mechanical stimuli such as the scratching of tags in the neck or the rubbing of collar interlinings, among other things. Seams that are not processed properly can also lead to skin irritations. Light clothes can cause excessive sweating. As a consequence the wet skin is more sensitive to mechanical attacks and irritations can then also occur. Furthermore the mixture of sweat and textile dust is an aggressive medium leading to irritated human skin. This issue appears mainly among textile workers. Finally, 'scratchy' wool, which means wool fibres with a diameter of 30 μm and above, can cause skin irritations. Those who are already predisposed towards atopic skin conditions suffer most with this.

An allergy caused by textiles is rare when the following factors are taken into account: the long lasting exposure to textiles that humans experience from birth to

© Woodhead Publishing Limited, 2011

death; the production and use of billions of textiles; and the frequency of other allergies caused by pollen, food such as strawberries and drugs such as penicillin. Due to the close contact between humans and their clothing, textiles are like a second skin. Thus it becomes understandable that all allergies caused by textiles belong to the contact allergy category. Only one to two per cent of all cases of contact allergies seen in German hospitals are caused by textiles, usually by dyes.

Allergies are not caused by the textile fibres, regardless of whether these are natural or synthetic, but by substances used during textile production. There are a number of defined substances and substance groups known to cause allergies. In detail those substances are formaldehyde, the metals nickel, chromium and cobalt, and organic dyes.

In the textile industry formaldehyde is found mostly in the form of formaldehyde resins, which are used as special finishing agents to create textiles with dimensional stability, easy-care characteristics or crease resistance. Under certain conditions, such as elevated temperature, the resins based on formaldehyde can release formaldehyde. The quantity of the formaldehyde released is dependent on the temperature in question. In the market there exist many textile products that release only a very small amount (i.e. less than 75 ppm; note: ppm = mg/kg) or no formaldehyde at all.

The amount of released formaldehyde which affects the skin while wearing the clothes, is less than that found under laboratory conditions. One reason for this observation is that not all of the released formaldehyde will be absorbed from the skin: some will instead disappear into the air. Some medical research suggests that a quantity of 30 ppm and above of free formaldehyde is necessary to cause an allergic reaction. Other opinions say that for pre-sensitised people much less formaldehyde is enough to cause an allergy.

In Germany there are no strict legal regulations concerning formaldehyde in textiles. Only products with a content of 0.15% = 1500 ppm and above,[1] which represents an unrealistically high content for textiles, must be marked accordingly.

Some metals such as nickel, chromium and cobalt are well known as allergens. In particular, nickel is known to provoke contact dermatitis in many cases and may be considered as the most prominent contact allergen. The so-called 'jeans button allergy' has become infamous in this respect. In textile products nickel can be found in metallic accessories such as zippers, buttons and rivets, and sometimes also in printed textiles. In this case the source is abrasion from nickel-plated print rollers. This type of nickel contamination can be easily washed out of textiles.

Nickel can be found often in other everyday commodities as costume jewellery, especially in cheap stud earrings, and glasses frames. A cross-reaction with nickel containing food as cocao, chocolate or nuts is possible.

In the European Union there are strict limits on the level of nickel release from metallic commodities, textiles included. The Directive 94/27/EC amended by Commission Directive 2004/96/EC limits the nickel release of commodities to ≤ 0.5 µg/cm^2/week over a period of 2 years.

© Woodhead Publishing Limited, 2011

In addition to nickel, chromium and cobalt can also be found in specific textile dyestuffs. The metals are bound very strongly to the dyestuff and to the textile fibre. This means that these metals will not cause an allergy if the dyeing process has been carried out correctly.

A number of disperse dyes are known to be allergenic. Dispersion dyes form a specific class of dyes, used for colouring the synthetic fibres polyester, polyamide and acetate. Most of them are azo- or anthraquinone compounds, and due to their lipophilic property they are not water soluble but are dispersed in the dye bath. They have an affinity to the similarly lipophilic synthetic fibre material and migrate during the dyeing process into the fibre material. When the textiles are worn, not enough fixed dyes can reach the skin and be absorbed. When this happens with any allergenic disperse dyes a contact dermatitis will occur. In the past two allergies caused by disperse dyes reached nearly epidemic proportions: In the 1970s the so-called 'stockings colour allergy' was common, while in the 1990s this was replaced by the 'leggings allergy'. Both occurrences were caused by colouring with allergenic disperse dyes.

The following dyes are said to be allergenic according to Oeko-Tex® Standard 100: Disperse Blue 1, 3, 7, 26, 35, 102, 106 and 124; Disperse Brown 1; Disperse Orange 1, 3, 37 and 76; Disperse Red 1,11 and 17; Disperse Yellow 1, 3, 9, 39 and 49. The former governmental BgVV Working group 'Textiles' judged eight dispersion dyes to be allergenic in 1993. These are Disperse Blue 1, 35, 106 and 124; Disperse Orange 3, and 37 = 76; Disperse Red 1; and Disperse Yellow 3. Since then German governmental institutions as BfR (Bundesinstitut fuer Risikobewertung – the Federal Institute for Risk Assessment) have recommended that these eight disperse dyes should not be used.

Allergenic disperse dyes are not banned by law either in Germany or in the EU as a whole. Nevertheless, in Germany, the law §30 LFGB (German Food and Feed Code) prohibits in a general clause the use of harmful substances in commodities.

In very rare cases consumers experience contact dermatitis caused by silk articles. The reason for this is the presence of residue of the silk gum sericin, a natural protein for glueing together the silk fibres in the cocoon of the silk worm. It is a result of poor methods in the production of the silk fabric, when the silk degumming has not been carried out properly.

A special kind of contact allergy is the so-called latex allergy. Properly speaking the latex allergy is a type 1 allergy, the immediate-type allergy caused by a hypersensitivity of skin cells coming into contact with products made from natural latex such as rubber gloves or elastic textile rubber threads.

11.4 Ways to minimise and avoid allergies caused by textiles

As reported in the previous section, allergy-causing substances in textiles are already quite well known. It has therefore become possible to avoid most of

© Woodhead Publishing Limited, 2011

them completely in the production of the textiles or at least to diminish their allergenic potential by applying modern, newly developed textile auxiliaries. As an example in the case of dyeing synthetic fibres with disperse dyes, complete avoidance of allergies is possible simply by not using these types of dyes, since they are known to cause allergies. Again, in the case of nickel allergy, complete avoidance is also possible by not using nickel-releasing metallic accessories as buttons or zippers.

The allergenic potential of fabrics finished with formaldehyde resins is possible by using resins that release very little or no formaldehyde. The results of the development by the chemical industry of resins that release less formaldehyde were remarkable.

There is one problem that must be addressed: how to find such optimized non-allergenic textiles? The solution can be found in textiles certified with reliable Eco- or Consumer Safety Labels. First, the Oeko-Tex® Standard 100 label (Fig. 11.1) must be mentioned. This label was introduced in 1992 by the International Association for Research and Testing in the Field of Textile Ecology (Oeko-Tex®), Zürich, Switzerland. The Oeko-Tex® Standard 100 mark is undoubtedly the market leader with more than 80 000 certificates issued. In 2009 alone more than 10 000 certificates were issued. The label is accepted globally and is the most common textile eco-mark worldwide. It stands for 'Confidence in Textiles'.

From the very beginning the Oeko-Tex® Standard 100 banned the use of allergenic disperse dyes and restricted the use of formaldehyde more rigorously than the well known Japanese Law 112 from 1972. Chromium(VI) was also banned from textiles and a regulation with the aim of reducing the release of sensitising heavy metals such as nickel, chromium et cetera was implemented.

Table 11.1 gives an overview of the criteria and limits required by the Oeko-Tex® Standard 100. Four product classes are identified, with different limits for each: baby, direct skin contact, textiles without direct skin contact, and decoration material. With regard to Table 11.1 and Table 11.2 it is clear that within

11.1 Oeko-Tex® Standard 100 label.

© Woodhead Publishing Limited, 2011

Table 11.1 Criteria applied for Oeko-Tex® Standard 100 certification

Constituent/property	Product class			
	I, baby	II, in direct contact with skin	III, with no direct contact with skin	IV, decoration material
pH value	4.0–7.5	4.0–7.5	4.0–9.0	4.0–9.0
Formaldehyde (mg/kg)				
Law 112	Not detected	75	300	300
Extractable heavy metals (mg/kg)				
Sb (antimony)	30.0	30.0	30.0	
As (arsenic)	0.2	1.0	1.0	1.0
Pb (lead)	0.2	1.0	1.0	1.0
Cd (cadmium)	0.1	0.1	0.1	0.1
Cr (chromium)	1.0	2.0	2.0	2.0
Cr(VI)	Under detection limit			
Co (cobalt)	1.0	4.0	4.0	4.0
Cu (copper)	25.0	50.0	50.0	50.0
Ni (nickel)	1.0	4.0	4.0	4.0
Hg (mercury)	0.02	0.02	0.02	0.02
Heavy metals in digested sample (mg/kg)				
Pb (lead)	45.0	90.0	90.0	90.0
Cb (cadmium)	50.0	100.0	100.0	100.0
Pesticides (mg/kg)				
Sum (incl. PCP/TeCP)	0.5	1.0	1.0	1.0
Chlorinated phenols (mg/kg)				
Pentachlorphenol (PCP)	0.05	0.5	0.5	0.5
'Tetrachlorphenol (TeCP, sum)'	0.05	0.5	0.5	0.5
Phthalates (wt%)				
'DINP, DNOP, DEHP, DIDP, BBP, DBP DIBP'				
Sum	0.1			
'DEHP, BBP, DBP DIBP'				
Sum		0.1	0.1	0.1
Organic tin compounds (mg/kg)				
TBT	0.5	1.0	1.0	1.0
TPhT	0.5	1.0	1.0	1.0
DBT	1.0	2.0	2.0	2.0
DOT	1.0	2.0	2.0	2.0
Other chemical residues				
Orthophenylphenol (OPP) (mg/kg)	50.0	100.0	100.0	100.0
Arylamines (mg/kg)	None			
PFOS ($\mu g/m^2$)	1.0	1.0	1.0	1.0
PFOA (mg/kg)	0.1	0.25	0.25	1.0

© Woodhead Publishing Limited, 2011

Table 11.1 Continued

Constituent/property	Product class			
	I, baby	II, in direct contact with skin	III, with no direct contact with skin	IV, decoration material
Dyes				
Cleavable arylamines			Not used	
Carcinogens			Not used	
Allergens			Not used	
Others			Not used	
Chlorinated benzenes and toluenes (mg/kg)				
Sum	1.0	1.0	1.0	1.0
Polycyclic aromatic hydrocarbons (PAH) (mg/kg)				
Benzo[a]pyrene	1.0	1.0	1.0	1.0
Suml 10	10.0	10.0	10.0	10.0
Biologically active products				
			None	
Flame retardant products				
General			None	
'PBB, TRIS, TEPA, pentaBDE, octaBDE'			Not used	
Colour fastness (staining)				
To water	3	3	3	3
To acidic perspiration	03-Apr	03-Apr	03-Apr	03-Apr
To alkaline perspiration	03-Apr	03-Apr	03-Apr	03-Apr
'To rubbing, dry'	4	4	4	4
To saliva and perspiration	Fast			
Emission of volatiles (mg/m^3)				
Formaldehyde (50-00-0)	0.1	0.1	0.1	0.1
Toluol (108-88-3)	0.1	0.1	0.1	0.1
Styrol (100-42-5)	0.005	0.005	0.005	0.005
Vinylcyclohexen (100-40-3)	0.002	0.002	0.002	0.002
4-Phenylcyclohexene (4994-16-5)	0.03	0.03	0.03	0.03
Butadiene (106-99-0)	0.002	0.002	0.002	0.002
Vinylchloride (75-01-4)	0.002	0.002	0.002	0.002
Aromatic hydrocarbons	0.3	0.3	0.3	0.3
Organic volatiles	0.5	0.5	0.5	0.5
Determination of odours				
General			No abnormal odour	
SNV 195 651 (modified)	3	3	3	3
Banned fibres				
Asbestos			Not used	

the Oeko-Tex® Standard 100 criteria restrictions are imposed in order to fully avoid or at least to minimise allergies caused by textiles:

- Ban of the use of allergenic disperse dyes

© Woodhead Publishing Limited, 2011

Table 11.2 Dyestuffs classified to be allergenic, according to Oeko-Tex®

C.I. Generic name	C.I. Structure number	CAS-No.
C.I. Disperse Blue 1	C.I. 64 500	2475-45-8
C.I. Disperse Blue 3	C.I. 61 505	2475-46-9
C.I. Disperse Blue 7	C.I. 62 500	3179-90-6
C.I. Disperse Blue 26	C.I. 63 305	
C.I. Disperse Blue 35		12222-75-2
C.I. Disperse Blue 102		12222-97-8
C.I. Disperse Blue 106		12223-01-7
C.I. Disperse Blue 124		61951-51-7
C.I. Disperse Brown 1		23355-64-8
C.I. Disperse Orange 1	C.I. 11 080	2581-69-3
C.I. Disperse Orange 3	C.I. 11 005	730-40-5
C.I. Disperse Orange 37	C.I. 11 132	
C.I. Disperse Orange 76	C.I. 11 132	
C.I. Disperse Red 1	C.I. 11 110	2872-52-8
C.I. Disperse Red 11	C.I. 62 015	2872-48-2
C.I. Disperse Red 17	C.I. 11 210	3179-89-3
C.I. Disperse Yellow 1	C.I. 10 345	119-15-3
C.I. Disperse Yellow 3	C.I. 11 855	2832-40-8
C.I. Disperse Yellow 9	C.I. 10 375	6373-73-5
C.I. Disperse Yellow 39		
C.I. Disperse Yellow 49		

- Strict limits on the nickel release of metallic accessories
- Strict limits on formaldehyde release from formaldehyde resins.

An important rule of the Oeko-Tex® Standard 100 is that all components of a textile, including linings, sewing threads, prints, zippers, etc. must fulfil the criteria listed above in Table 11.1 and Table 11.2. That means that even small components in textiles are not allowed to contain harmful substances, including allergenic substances. As a result Oeko-Tex® Standard 100 certified textiles guarantee a high level of protection to the consumer from allergic reactions caused by textiles.

Alongside the Oeko-Tex® Standard 100 label, other eco- or consumer safety labels also exist, for which this basic principle also holds. One label that should be mentioned is the 'Medically Tested/Tested for Toxins' label devised by the Society for the Promotion of Skin-Tolerant Textiles, Denkendorf, Germany. A double-stage effect-related skin tolerance test (cytotoxicity test and keratinocytes test) combined with a limit-oriented toxin test provides the basis for the labelling of textiles. The toxin test broadly corresponds to the Oeko-Tex® Standard 100. The cytotoxicity test shows whether cells will be impaired by the textile. The keratinocytes test measures the skin irritation potential of the textile. To date it is one of the strictest known skin-tolerance tests,

© Woodhead Publishing Limited, 2011

and has been developed based on methods used in the qualifying examination for medical products.

A third well-established label, 'Toxproof', is awarded by TÜV Rheinland, Cologne, Germany. It is also based largely on the criteria of the Oeko-Tex® Standard 100. However, fewer disperse dyes are banned by the Toxproof criteria. Nevertheless these criteria ensure that textiles bearing the Toxproof label do not cause contact allergies in humans. The advantage of the three consumer safety labels is that testing is done by independent testing laboratories and certification is applicable for all sorts of textiles including those made from synthetic fibres.

Besides the major labels mentioned above, some other eco-labels have also arisen, based more or less on the same criteria as the Oeko-Tex® Standard 100, from companies such as mail-order houses or textile retailers. Eco-labels and also exist are exclusively for textiles made from natural fibres. These labels consider not only toxins but also, exceptionally, take into account ecological growth and social aspects. The best known of these from an international perspective are the labels 'Global Organic Textile Standard' (GOTS)[3] and 'Naturtextil IVN zertifiziert BEST'.[4]

11.5 Testing for allergy-causing substances

An allergy suspected of being caused by textiles must be investigated. It is first necessary to clarify whether the textile could feasibly be the root cause of the allergy, based on the location and appearance of the allergic reaction. Any effects simply caused by mechanical skin irritation, such as scratching tags, must be excluded. If it seems to be confirmed that an allergy has been caused by the textile, testing must be carried out to determine the allergenic substance.

As allergies caused by textiles belong to type IV, the delayed-type allergy, the epicutane test is the instrument of choice. The epicutane test, also called patch test, is a common medical test to find out whether a specific substance causes allergic reaction of the skin. The substances under suspicion should be identified through the patient's medical history, or in the case of textiles through knowledge of the chemicals used in production. The test is performed as follows: Patches are prepared with the suspected substances and fixed to the patient's back. The occlusive patches remain there for 48 hours. Twenty-four, 48 and 72 hours after the removal of the patches, the test areas of the skin are evaluated and examined for signs of erythema or oedema.

11.5.1 Nickel

The so-called 'jeans button allergy' is easy to identify. This type of allergy is typified by a circular red area appearing on the skin at those points where the skin had direct contact with the button or rivet containing nickel. A corresponding nickel patch test is available. Other harmful substances are more difficult to identify.

© Woodhead Publishing Limited, 2011

11.5.2 Disperse dyes

For comprehensive testing purposes further knock-out criteria must be considered: no appearance of disperse dyes in uncoloured textiles, in coloured or printed textiles from 100% cotton or viscose is expected. However, coloured fabrics made of a mixture of cotton and viscose with synthetic fibres can contain disperse dyes. One reason is that only synthetic fibres such as polyester, polyamide (e.g. nylon) or acetate can be coloured with disperse dyes. Care should be taken with stockings and leggings: these kinds of textiles are commonly dyed with disperse dyes. For an epicutane test for the most important allergenic disperse dyes, patches are available. In addition, a patch test with the suspected textile should also be carried out. The patch test with the textile may not show any positive reaction, as a result of low availability of the substance in question. In this case the epicutane test can be repeated under aggravated conditions after scraping off the horny layer of the skin. Another possibility is testing the suspicious textile for allergenic disperse dyes in a special chemical laboratory under chemical analytical conditions e.g. according to DIN 54231:2005-11 'Textiles – detection of disperse dyestuff'.

11.5.3 Formaldehyde

Nowadays allergies caused by formaldehyde in textiles have become quite rare, since current formaldehyde resins used in textile production only contain low concentrations of formaldehyde. Nevertheless, people who are sensitised to formaldehyde can experience allergic reactions even as a result of contact with the lowest concentrations of formaldehyde. Textiles that contain formaldehyde can be identified by labels such as 'no iron', 'shrink-resistant', 'easy-care' and 'crinkle free'.

The epicutane test for formaldehyde is common in dermatological clinics. Suitable patches for formaldehyde testing are available. Suspicious textiles can be reliably tested for formaldehyde content in chemical laboratories. The tests can be done according to ISO 14184-1:1998 'Textiles – Determination of formaldehyde, Part 1: Free and hydrolyzed formaldehyde (Water extraction method)' or AATCC 112-1998. The latter of these supplies proportionally higher results because the extraction of the formaldehyde is carried out at a slightly higher temperature (49°C instead of 40°C). Apart from that both tests follow the same analytical principle: The extracted formaldehyde is converted by using acetylacetone reagent to a yellow coloured compound, the concentration of which is measured spectroscopically.

The trend in testing is moving in the direction of effect-based testing for allergens in textiles to add to the current substance-based testing for harmful substances. A method of this sort, a cell culture test using immune cells, has been developed at the Institute for Hygiene and Biotechnology (IHB) at the Hohenstein Institute, Boennigheim, Germany.[5]

© Woodhead Publishing Limited, 2011

11.6 Medical textile applications

Great value is already placed on textiles without harmful substances, e.g. textiles without allergenic chemicals; this is still more important for medical textiles. In this context, textiles are in contact with people who are already debilitated by illness. In the case of bandage materials, there is not even an intact skin barrier.

The application of textiles in the field of medicine is multifarious and reaches from plasters, through occupational clothing to the interior decoration of hospital rooms. Plasters, wound dressings, elastic bandages, and surgical stockings of various sorts are employed in direct human contact. Physicians, nurses, care assistants and others wear occupational clothing from top to toe. In some areas in the hospital employees must wear protective clothing such as scrubs or surgical masks.

In the operating theatre various types of medical drapes are used. The main uses of textiles in hospital wards are in hospital beds as mattresses, bed sheets, pillows and blankets. Finally, textiles, for example in the form of curtains, are also used for the interior decoration of hospital rooms. The composition and production of textiles is just as diverse as their use, ranging from pure unfinished cotton to polyurethane coated polyester. Consequently, the likelihood of introducing harmful, e.g. allergenic, substances with the textiles is also variable. Faced with this variety of different 'medical textiles' it is important that the purchasing agents demand textiles without harmful substances, and especially without allergenic substances. The buyer would be best served by textiles certified with a reliable eco- or consumer safety label.

Two medical textile examples will be considered more in detail: scrubs and medical drapes and support and thromboembolic stockings. *Scrubs and medical drapes* are protective textiles which are used in the operating theatre. Both types of textiles share a protective function and are both in close proximity to human skin. The fabric is usually made from a cotton/polyester mixture with a plain weave construction. Both articles are coloured in the same shade, predominantly in green or blue. From the allergic side the problem is the colouring of the polyester part. Thus the colouring must not be carried out with disperse dyes that cause allergies

Support stockings and thromboembolic stockings belong to the same product class. Their shared task is to prevent a thrombosis. For this purpose the stockings must apply pressure to the legs. As a consequence these stockings have a very intensive contact with human skin. It is a must that the textile material used does not harm the wearer.

The necessary pressure is attained in textiles by using elastic threads. In the early days of the production of support stockings the elastic threads were made from natural latex. With no other material available, people were exposed to the risk of a potential latex allergy. Later on elastic threads made from artificial rubber were used. However this material also caused impairment of health due to additives such as MBT (2-mercaptobenzothiazole) or thiurames. Nowadays,

© Woodhead Publishing Limited, 2011

unproblematic elastanes such as Spandex or Lycra® are used as elastic threads for the production of support stockings and thromboembolic stockings.

The continuous replacement of textiles containing potential allergens with less harmful materials is a good example to demonstrate the social responsibility of the textile industry towards the consumer. The difference between support and thromboembolic stockings is mainly fashion: Support stockings are coloured fashionably by using non allergenic dyes.

11.7 Sources of further information and advice

The subject 'Allergies caused by textiles' is manifold. It can be approached from different angles such as from the medical, the chemical or the textile point of view. Generally, the internet is recommended for initial further information, as this medium is gaining more and more importance as an accepted source of comprehensive and up-to-date knowledge.

In the area of medical science keywords such as allergy, contact allergy, textile allergy, allergy to clothing, allergic contact dermatitis to textile dyes etc. should be used as search terms. One book recommended is *Contact Dermatitis* by Etain Cronin.[6] In the chapter headed 'Clothing and textiles' several clinical case studies are presented – mostly between 1950 and 1975 – as well as a comprehensive list of further basic and scientific references.

For approaching the subject 'Allergy and textiles' more from the textiles perspective, the website of the German Federal Institute for Risk Assessment (BfR)[7] can be recommended as source of up-to-date information. Since 1992 there has been a working group studying allergenic substances in textile production. In the US the websites of the U.S. Environmental Protection Agency (EPA)[8] or the American Apparel and Footwear Association (AAFA)[9] might be considered.

Also of use are the websites of institutions awarding textile eco labels such as Oeko-Tex® Standard 100[10] or consumer safety labels such as Toxproof.[11] In their criteria lists one can find those substances causing textile allergies that are currently banned. Internationally operating testing institutes such as Hansecontrol,[12] SGS,[13] Bureau Veritas[14] or eco-Institut[15] also offer information on their websites about allergenic substances in textiles.

11.8 References

1 BGBL. I 1998, 33.
2 Oeko-Tex, Online publication: Limit values and fastness. Available: http://www.oeko-tex.com/OekoTex100_PUBLIC/content1.asp?area=hauptmenue&site=grenzwerte&cls=01 [Accessed 29 January 2010].
3 www.global-standard.org
4 www.naturtextil.com
5 Hohenstein Institute, Online publication (in German): Neues wirkungsbezogenes Prüfverfahren zur Bestimmung von Kontaktallergenen. Available: http://www.hohenstein.de/SITES/presse.asp [Accessed March 2009].

© Woodhead Publishing Limited, 2011

6 Cronin, Etain, *Contact Dermatitis*. Churchill Livingstone, London, 1980, ISBN 0 443 02014 0.
7 Homepage German Federal Institute for Risk Assessment (BfR), Available: http://www.bfr.bund.de [Accessed 25 May 2010].
8 Homepage http://www.epa.gov
9 Homepage http://www.apparelandfootwear.org
10 Homepage http://www.oeko-tex.com
11 Homepage http://www.tuv.com
12 Homepage http://www.hansecontrol.de
13 Homepage http://www.sgs.com
14 Homepage http://www.bureauveritas.com
15 Homepage http://www.eco-institut.de

© Woodhead Publishing Limited, 2011

12

Biofunctional textiles based on cellulose and their approaches for therapy and prevention of atopic eczema

U-C. HIPLER and C. WIEGAND,
Friedrich Schiller University of Jena, Germany

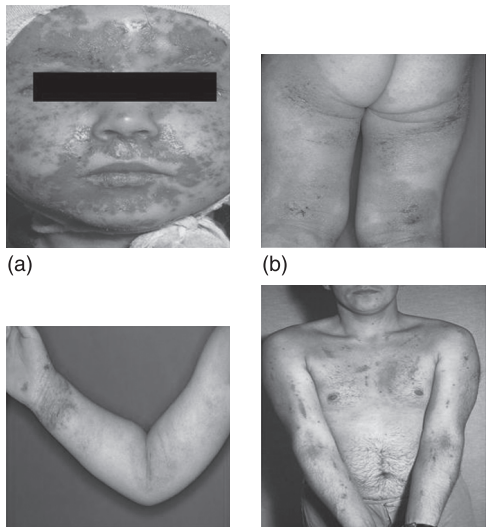
Abstract: Functional textiles have been gaining importance in medical applications and they play a critical role in inflammatory skin conditions such as atopic dermatitis and psoriasis, or in diabetic patients as well as in aged skin. Psoriasis vulgaris and atopic dermatitis are characterised by various different clinical and histological features depending on the stage of the disease. Antimicrobial therapy has been shown to be important for the treatment of atopic dermatitis. This chapter describes some of the features of atopic dermatitis and the benefits of two cellulose-based textiles, Lyocell and SeaCell®, for patients with dermatitis. The use of Lyocell as a nonwoven with biofunctional properties, and the capacity of SeaCell® to bind and absorb substances, including antimicrobials such as silver, is emphasised.

Key words: atopic dermatitis, biofunctional textiles, Lyocell fibres, SeaCell® textiles, antimicrobial therapy.

12.1 Introduction

Atopic dermatitis (AD), often also termed atopic eczema or atopic eczema dermatitis syndrome, is a chronic inflammatory skin disease that affects a large number of children and adults in industrialised countries.[1] In 47% of the affected children, the onset of AD occurs during the first six months of life, during the first year of life in 60%, and before the age of five years in almost 90%.[2] Of those children with manifestation before the age of two years, about 20% develop persistent AD, and 38% have intermittent symptoms by the age of seven years.[3] Predominantly AD afflicts infants and children, however, in adults with AD 16.8% had onset after adolescence.[4] The clinical pattern of AD varies with age (Fig. 12.1). Infants typically present erythematous papules and vesicles on the cheeks, forehead or scalp, which are intensely itchy. The childhood phase, typically occurring from two years of age to puberty, exhibits more lichenified papules and plaques representing the more chronic disease and involving the hands, feet, wrists, ankles, armpits, and hollows of knees. The adult phase of AD begins at puberty and frequently continues into adulthood. Predominant areas of involvement include the flexural folds, the face and neck, the upper arms and back, and the dorsa of hands, feet, fingers, and toes. The eruption is characterised by dry, scaling erythematous papules and plaques and the formation of large lichenified plaques from lesional chronicity.[1,5]

© Woodhead Publishing Limited, 2011



12.1 Age-related variation in the clinical characteristics of atopic dermatitis: (a) infancy stage; (b, c) childhood stage; (d) adult stage.

AD presents a complex disease relying on the interplay of several factors.[5] A number of candidate genes have been identified that may contribute to disease manifestation.[6] Still, genetic effects alone cannot explain all cases of AD observed. The results of studies of migrant populations, for example, show that Jamaican children living in London are twice as likely to have atopic dermatitis as are Jamaican children living in Jamaica. Furthermore, the risk of AD in smaller families and among higher social classes is increased; and the prevalence in some countries is rising.[5] These observations suggest a crucial role for environmental factors in mediating disease development.[7] Whereas allergens such as house-dust mites and foods may be important in some cases, non-allergic factors such as rough clothing, exposure to irritants that disrupt the function of the skin barrier, *Staphylococcus aureus* infections or colonisation with *Malassezia* spp., may also be important.

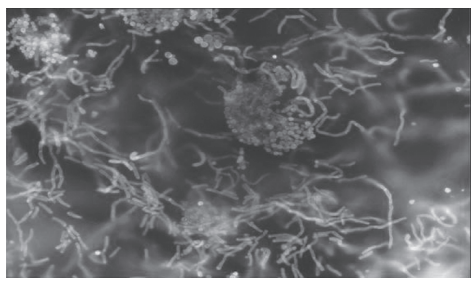
12.2 The role of microbial infections in atopic dermatitis

Patients with AD exhibit an increased susceptibility to cutaneous bacterial, fungal and viral infections.[8,9] The microbial flora of atopic skin shows striking differences compared to normal skin. In more than 90% of patients with AD, colonisation with *Staphylococcus aureus* can be found in comparison to less than 10% in healthy individuals.[10] The carriage rate of *Staphylococcus aureus* for AD patients was found to be >90% for inflammatory lesions and 76% for uninvolved skin.[11] Furthermore, the quantity of *Staphylococcus aureus* is linked to the severity of

© Woodhead Publishing Limited, 2011

eczema[11,12] so that topical and systemic antibacterial drugs are often used to keep the skin under control.[13] In recent years, there has been growing evidence that yeasts belonging to the *Malassezia* genus may be involved in the pathophysiology of AD. Some studies also suggested that *Candida albicans* has a possible pathogenic role.[12,14] These yeasts (Fig. 12.2) are considered to be part of the normal skin flora; however, they might trigger several cutaneous and systemic diseases. *Malassezia* has been associated with pityriasis versicolor, seborrhoic dermatitis, dandruff, folliculits and atopic dermatitis. AD patients, particularly those with dermatitis localised in the head and neck region (areas of the body known to be heavily colonised by *Malassezia*), usually have an increased sensitisation to the yeast, by both the cellular and humoral immune response.[15]

So far, the underlying immunological mechanisms of the susceptibility of atopic skin to microbial infection and colonisation are still unclear.[16] Recent evidence suggests that impaired innate immune mechanisms contribute to the predisposition of AD patients to skin infections. The innate immune system of the epidermis is the first line of defence against invasion by microorganisms, which gain entry after the skin is damaged. Antimicrobial peptides form part of this defence system.[9] The inducible antimicrobial peptides, human cathelicidin LL-37, human beta defensin (HBD)-2, and HBD-3, were shown to be expressed at a significantly lower level in skin lesions of AD patients compared with lesional skin in psoriasis.[17,18] A reduced production significantly weakens the defence system and leads to an increased colonisation and infection rate.[19] The innate skin defence system of AD patients is further compromised by a deficiency of dermacidin-derived antimicrobial peptides


(a)

(b) (c)

12.2 (a) *Malassezia* spp. stained with blankophor; (b) *Candida* spp. stained with blankophor, (c) *Candida* spp. growth on rice agar.

© Woodhead Publishing Limited, 2011

in the sweat, which was found to correlate with infections.[16] Dermacidin, a peptide with no homology to other antimicrobial peptides, is specifically and constitutively expressed in sweat glands in the dermis of the skin, secreted into sweat and transported to the epidermis surface. In healthy individuals, a significant reduction in viable bacterial cells on the skin surface occurs after sweating but this was not observed in the case of AD patients.[16]

12.3 Skin barrier function and increased sensitivity to irritants

AD is further characterised by dry skin and increased transepidermal water loss.[20] Ceramides serve as the major water-retaining molecules in the extracellular space of the cornified envelope. A reduced content of ceramides has been reported in the stratum corneum of both lesional and uninvolved skin in patients with AD.[1,21] Alterations in the pH levels have also been found in patients with AD and are thought to impair lipid metabolism in the skin.[22] Furthermore, changes in the expression of stratum corneum chamotryptic enzyme (SCCE) may contribute to the breakdown of the skin barrier in AD patients.[23] This would facilitate penetration of irritants, allergens, and microorganisms which afterwards trigger an inflammatory response thus contributing to the cutaneous hyper-reactivity characteristic for AD. Treatment on the basis of disease severity includes the addition of multiple therapeutic agents such as topical corticosteroids, topical calcineurin inhibitors, oral antihistamines (recommended for their sedative effect), topical doxepin (relief from itching), antibiotic agents, UV light, and immunosuppressive agents.[1,5] Basic therapy of AD should also comprise optimal skin care, addressing the skin barrier defect with regular use of emollients and skin hydration.[1]

Non-specific irritants for AD patients also include contactants such as clothing made from occluding or irritating synthetic material or wool. Direct contact of the skin with wool induces a characteristic itching in patients with AD that is most likely caused by the prickly nature of wool fibres.[24,25] Furthermore, the surface structure and diameter of fibres has a significant influence on how well the respective fabrics of wool or synthetic are tolerated by the patient.[24,26] A direct relation between fibre diameter and extent of irritation has been observed. The mechanically mediated skin irritation is increased with fibre roughness caused by the increased penetration of the fibre into the skin.[27,28] Good skin tolerance has been found for textiles from cotton.[27] Therefore, AD patients are often advised to wear cotton clothes. However, cotton threads consist of short and irregular fibres with a length of 1–3 cm that produce microscopic stubs[29] and recent studies suggested that cotton fibres when moistened may irritate and scratch the skin causing the deterioration of eczematous lesions in the patients with AD.[13] Hence, there is the demand for manufacturing new fabrics with low fibre diameter and high quality to reduce irritative potential and make them more suitable for patients with AD.

© Woodhead Publishing Limited, 2011

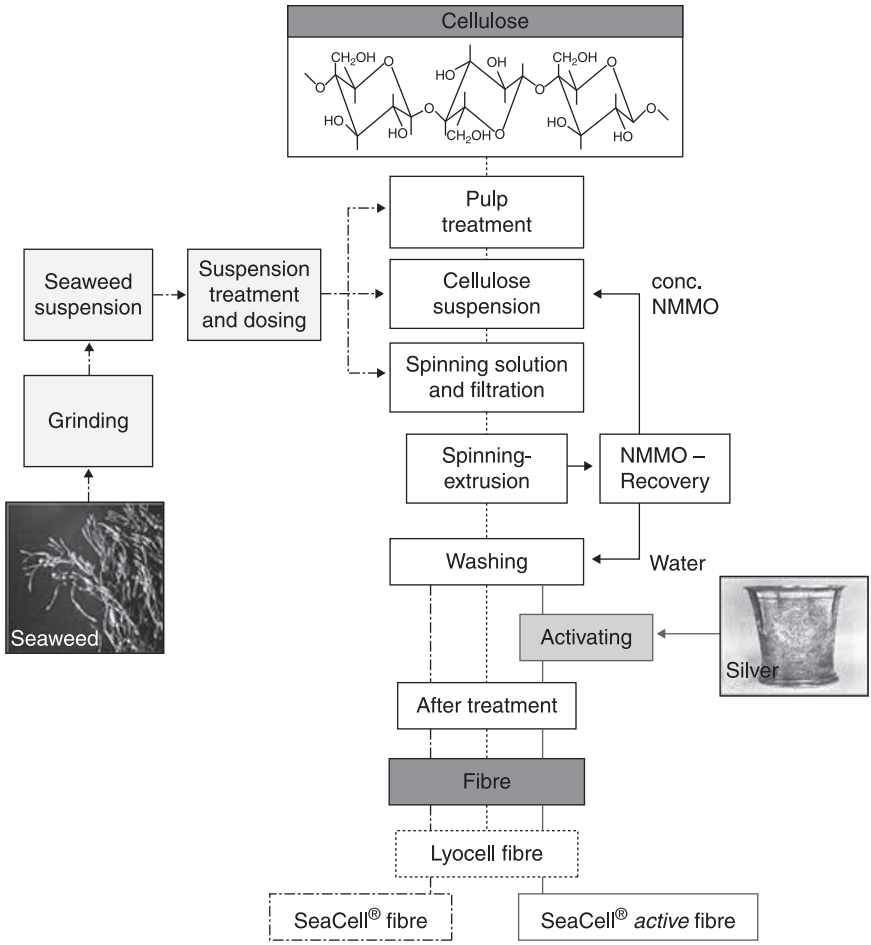
12.4 Lyocell fibres for antimicrobial therapy

Cellulose materials are still the most used fibres.[30] Compared to synthetic polymer fibres they possess the advantage of being fully biocompatible and compostable. Moreover, cellulose is produced by green plants and thus derives from a renewable, natural source.[31] The demand for apparel fabrics steadily expanded during the twentieth century and is most likely to continue growing. Yet, the possibilities to enhance cotton fibre production are limited. Hence, there is considerable potential for a further increase in the production of 'cellulosics', especially viscose (rayon) fibres.[31] However, viscose/modal fibre production is based on the derivatisation of cellulose using carbon disulfide (CS_2).[32] This process is environmentally challenging as it uses not only CS_2 but also a rather high load of dissolution and spinning bath chemicals.[33] Therefore, the search for alternative processes to generate cellulosic fibres is ongoing. The most promising of the developments for a new competitive cellulose-fibre technology is the Lyocell process.[33]

The Lyocell process (Fig. 12.3) is an environment-friendly, economically viable, product-enhancing and highly flexible alternative for the manufacture of cellulose fibres. In contrast to the viscose process, no derivatisation steps such as alkalisation or xanthation are required to dissolve the cellulose. Instead, a melt of *N*-methylmorpholine-*N*-oxide monohydrate (NMMO) at elevated processing temperatures (approx. 100°C) is used as a solvent. The spinning solution is processed in a combined dry/wet spinning step (air gap) to form fibres and shaped cellulose articles.[34,35] During this spinning process, the solvent required to produce the spinning solution is simply washed out and almost completely recycled with a recovery rate of 99.3% even on industrial scale. Thus, very few process chemicals are applied, and ideally NMMO and water are completely recycled, which are important economic and ecological factors. In comparison with cotton and viscose, the Lyocell process therefore constitutes a significantly lower environmental burden (reviewed in Ref. 31). This is mainly due to the low toxicity of the cellulose solvent NMMO and its biodegradability.[36] The flexibility of the process in terms of the cellulosic raw materials is another major advantage. Hypothetically, paper grade pulp, unbleached chemical pulp, cotton, rayon fibres or even waste paper can be employed as raw materials for Lyocell fibre production (reviewed in Ref. 31).

The generic term 'Lyocell' is commonly used to designate the industrial process, the fibres produced therein, and the NMMO/cellulose mixtures. The manufacturers use different brand names for their products: Tencel (Lenzing AG, Austria), Alceru (TITK Rudolstadt, Germany), and Newcell (Akzo Nobel, The Netherlands). Industrial scale production facilities for cellulosic fibres from NMMO solutions were set up during the 1990s (reviewed in Ref. 31). Hence, it is definitely justified to consider Lyocell as a well-established and important new member in the family of functional textile fibres. Based on Lyocell technology,

© Woodhead Publishing Limited, 2011



12.3 The Lyocell process (Lyocell fibre) offers the possibility to blend cellulose with a second polymer prior to regeneration such as alginate from seaweed (SeaCell® fibre). Furthermore, the blend fibres of cellulose and seaweed show a high absorption capacity for metal ions and thus enable the incorporation of antimicrobial metals like silver in the core of the fully formed fibre in an activating step.

other cellulosic products, such as films, beads, membranes and filaments, are currently being developed or are already being commercially produced (reviewed in Ref. 31).

Lyocell fibres consist of regenerated cellulose (cellulose II). They are characterised by high crystallinity, long crystallites, high degree of orientation, and well-oriented amorphous regions,[31,37] resulting in a very high dry and wet tensile strength, a high wet modulus and high loop tenacity.[31,38] A typical attribute

© Woodhead Publishing Limited, 2011

of Lyocell fibres is their tendency towards fibrillation (pilling).[31,37] This immanent feature, but also other fibre properties, can be influenced by process and spinning parameters, especially by finishing conditions, and can even be used to achieve special optical effects and wear properties (reviewed in Ref. 31). Thus, Lyocell fibres can be advantageously utilised in hetero-yarns, specialty textiles, and nonwoven fabrics with specific properties[31,38] presenting a promising basic fibre for the production of biofunctional textiles. Another auspicious aspect of the solvent-based process is the potential for blending cellulose with a second polymer component prior to regeneration. Examples are blend fibres of cellulose and carbon black for conductive and moisture-sensing fibres,[39] cellulose and ceramic materials for special ceramic devices,[40] and cellulose with water-absorbing polymers for superabsorbing materials[41] or with seaweed for health-promoting effects.[42]

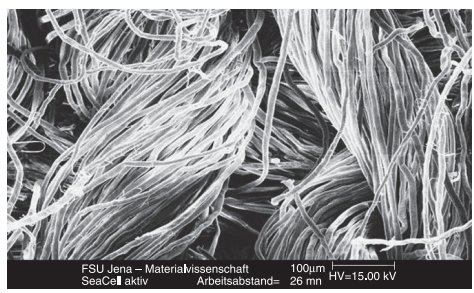
12.5 SeaCell® textiles for antimicrobial therapy

The SeaCell® fibres (SeaCell GmbH Rudolstadt, Germany) are manufactured by adding finely ground seaweed either as a powder or as a suspension in one of the process steps preceding the spinning of the cellulose solution (Fig. 12.3). Mainly the brown algae *Ascophyllum nodosum* and/or the red algae *Lithothamnium calcareum* are used as additives.[42,43] The resulting SeaCell® fibre exhibits a remarkably high tensile strength in dry and wet condition as well as negligible shrinking. Based on the good physical properties of the textiles, fabrics made from SeaCell® fibres offer high dimensional stability in addition to high wear comfort.[43] One special feature of the SeaCell® fibre is its capacity to bind and absorb substances.[44] During the activation of the fibres, bactericidal metals like silver, zinc, copper, and others can be absorbed by the fully formed cellulosic fibre through metal absorption. Unlike the commonly used method of incorporating the active ingredients in the spinning solutions, the manufacture of SeaCell® *active* offers the possibility of incorporating the substance permanently in the core of the fully formed fibre in an activation step. Impregnation tests with diluted metal salt solutions showed that SeaCell® fibre exhibits excellent sorptive properties regarding metals and/or metal ions. It can be assumed that the metals are bound by free carbonyl, carboxyl, and hydroxyl groups of the cellulose as well as of the incorporated seaweed.[45,46]

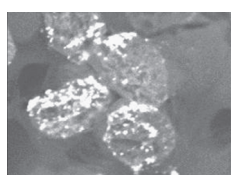
The development of new textiles designed to help prevent microbial colonisation with *Staphylococcus aureus* and yeasts presents a promising path in the treatment and maintenance of AD.[13] A new concept is the use of textiles with silver fibres. Worn on the skin the silver enrols its antimicrobial activity and has been shown to significantly reduce *Staphyloccous aureus* colonisation on the skin of AD patients.[47,48] The cellulose- and seaweed-based SeaCell® fibres can serve as a functional carrier for the active silver compound (Fig. 12.3). Silver (Ag^+) is effective against a broad range of microorganisms such as yeast, moulds and

© Woodhead Publishing Limited, 2011

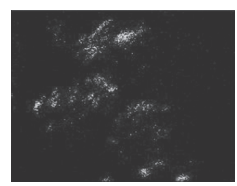
bacteria, including MRSA and VRE, when it is provided in appropriate concentration.[49–51] Silver ions are highly reactive; they react with inorganic compounds, organic acids, proteins, DNA and RNA. The microorganisms are killed by Ag^+ through various mechanisms of action, such as inhibition of cellular respiration, interference with DNA replication, and alteration of cellular membrane permeability.[49] In the demanding field of wound care silver-coated dressings have been demonstrated to be effective at killing a broader range of bacteria than cream-based silver applications while being less irritating than silver nitrate solution and better tolerated.[52] By incorporating silver into alginate fibres, it could be shown that antimicrobial activity against *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, *Escherichia coli* and *Candida albicans* can be increased.[53] In contrast to other silver products, where released silver is quickly inactivated by chloride and proteins on the skin surface or in wound exudates,[54] the SeaCell® *active* fibre (Fig. 12.4) provides a controlled, sustained release of silver. Because of the very low but sufficient leaching of silver ions from the SeaCell® *active* fibre, the antibacterial activity remains unchanged over time as shown for the washed fibres (60 wash cycles).[44] The excellent wearing comfort of the cellulosic fibre is not affected by the incorporation of silver.[44] Additionally, this fibre contains the minerals calcium, magnesium, and sodium which are known to play a key role in skin homeostasis.[55]



(a) Source: Institute of materials and technology, FSU Jena



(b)

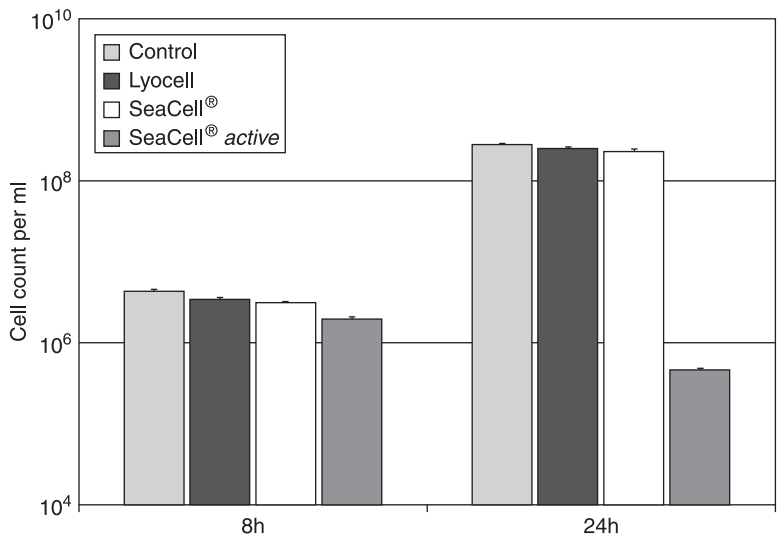


(c) Source: Zimmer AG, ITCF Denkendorf

12.4 Scanning electron microscope (SEM) picture of the SeaCell® *active* fibres (a) and assessment of cryogenic breaks of SeaCell® *active* fibres (b) to differentiate the distribution of silver at the break surface by energy-dispersive X-ray (EDX) analysis (c).

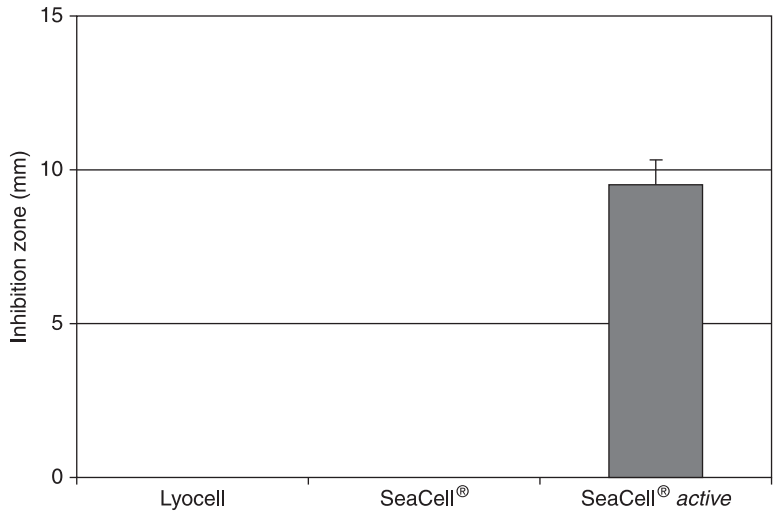
© Woodhead Publishing Limited, 2011

Bedding and textiles with minor concentrations of silver already show positive effects in the treatment of AD.[44,56] Silver-coated textiles were reported to significantly reduce *Staphylococcus aureus* colonisation after textile treatment even until after cessation of treatment.[57] The reduction of *Staphylococcus aureus* was found to be paralleled by a reduction of eczema severity, supporting the clinical experience that antiseptic treatment is essential for an efficient therapy of affected lesions in AD.[47,56] An *in vitro* test system could impressively demonstrate the antifungal and antibacterial effects of SeaCell® *active*.[44] *Candida albicans* is responsible for a widely encountered itching skin infection especially in skin folds. These fungal infections are associated with warm, moist and occlusive conditions, e.g. under the armpits, under the breasts, as well as in the genital and anal regions.[44] It could be shown that SeaCell® *active* achieved an excellent antifungal activity against different fungi from the *Candida* family (Fig. 12.5). Furthermore, *Staphylococcus aureus* is known as an aggravation factor in AD.[10–12] The bacterium is also responsible for other severe skin infections, and the wide spread of multi-resistant strains is becoming a major problem not only in dermatology.[58–60] The SeaCell® *active* fibres exhibited a high antibacterial activity (Fig. 12.6), the effect could be shown to be dose-dependent with the highest activity in the fibre with 100% of the active silver load.[44] Moreover, *in vitro* studies showed significant anti-oxidant properties of cellulosic materials. Free radicals such as superoxide anion or peroxynitrite are thought to play an important role as mediators of inflammation and tissue injury in diseases like AD.[61,62] The formation of ROS and



12.5 Antifungal activity against *Candida albicans* (DSM 11225) of different fabrics was determined after incubation of 8 and 24 h by counting yeast cells with a Neubauer cell counting chamber.

© Woodhead Publishing Limited, 2011



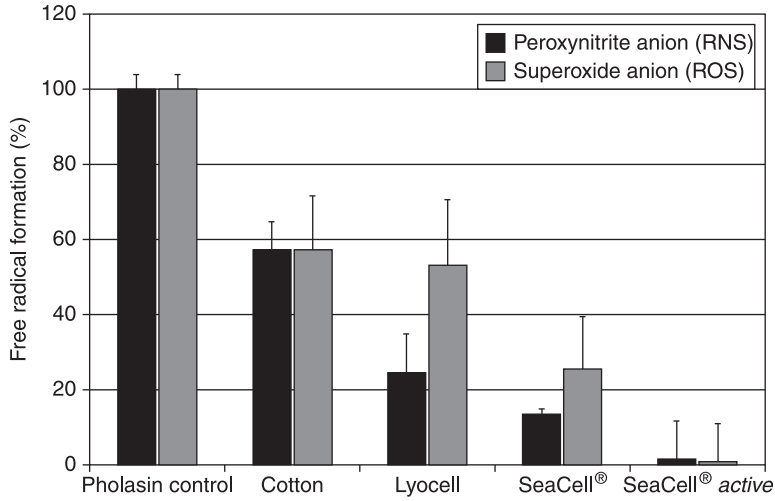
12.6 Antibacterial activity against *Staphylococcus aureus* (ATCC 22923) of different fabrics with an inoculum concentration of 105 cfu/ml. The cellulosic fabrics were cut into 6-mm diameter disks. These disks were then placed in the center of Mueller–Hinton agar (MHA) plates that had been inoculated with the test bacteria and incubated for 24 h at 37°C. Thereafter the zones of inhibition were measured.

RNS could be inhibited by cellulose fabrics (Fig. 12.7). Cotton and Lyocell achieved a similar scavenging capacity for ROS of 43% and 47%, while Lyocell performed better in the RNS test with 76% inhibition of radical formation compared to 43% for cotton. Additives increased the anti-oxidant properties of the Lyocell fibre. Thus, SeaCell® was able to inhibit ROS formation by 75% and RNS formation by 87%. SeaCell® *active* showed an almost complete scavenging capacity for ROS and RNS of 99%. These anti-oxidant properties are thought to at least partially contribute to the mode of action of biofunctional textiles.

12.6 Future trends and conclusions

New textile technologies have been developed with the goal of giving additional functionality to fabrics. The skin is the interface between the body and the environment. Each skin type has a specific skin physiology and is more or less adapted for protection against multiple stress factors.[44] Textiles are the tissues with the longest contact to the human skin.[44] They play a critical role especially in skin conditions with an increased rate of bacterial and fungal infections like atopic dermatitis and hyperhidrosis, and in diabetic patients and aged skin.[44,48] Hence, they present new interesting possibilities for therapeutic application and have been steadily gaining importance as treatment options. The increasing demand for ‘intelligent’, ‘biofunctional’ textiles led to the development of new

© Woodhead Publishing Limited, 2011



12.7 The capability of the tested fabrics to scavenge ROS and RNS was assessed using the chemiluminescent ABEL Antioxidant Test Kits specific for peroxynitrite and superoxide anion purchased from Knight Scientific Limited (Plymouth, UK). Both kits use Pholasin, a photoprotein isolated from the mollusc *Pholas dactylus*, which emits light in the presence of oxidants. The tests are based on a cell independent system and the necessary solutions to create free radicals that activate the Pholasin are provided. Measurements were run in 96-well microplates and luminescence was measured using the LUMIstar Galaxy plate reader (BMG Labtech, Germany).

fibres for clothing textiles with beneficial influence on the human organism.[44] Textiles have been improved to protect against UV radiation,[63] they may have integrated sensors to diagnose medical conditions,[64–66] or may be equipped with carrier molecules to release therapeutic compounds.[67,68] The development of textiles with antimicrobial and anti-oxidant capacity represents a promising path in the treatment of AD, as it might become a well accepted therapeutic alternative to steroid treatment.[29] Their success so far led to the inclusion of these textiles in the therapeutical standard for AD (Neurodermitis S2-Leitlinie) in 2009.[56]

12.7 References

1 Akdis CA, Akdis M, Bieber T, Bindslev-Jensen C, *et al*. (2006). Diagnosis and treatment of atopic dermatitis in children and adults: European Academy of Allergy, Asthma and Clinical Immunology/American Academy of Allergy, Asthma and Immunology/PRACTALL Consensus Report. *Allergy*, 61, 969–987.

2 Kay J, Gawkrodger DJ, Mortimer MJ and Jaron AG (1994). The prevalence of childhood atopic aczemy in a general population. *J Am Acad Dermatol*, 30, 35–39.

© Woodhead Publishing Limited, 2011

3 Illi S, von Mutius E, Lau S, Nickel R, Gruber C, *et al*. (2004). The natural course of atopic dermatitis from birth to age 7 years and the association with asthma. *J Allergy Clin Immunol*, 113, 925–931.
4 Ozkaya E (2005). Adult-onset atopic dermatitis. *J Am Acad Dermatol*, 52, 579–582.
5 Hywel CW (2005). Atopic Dermatitis. *N Engl J Med*, 352, 2314–2324.
6 Cookson WO and Moffat MF (2002). The genetics of atopic dermatitis. *Curr Opin Allergy Clin Immunol*, 2, 383–387.
7 Williams HC (1995). Atopic eczema – why we should look to the environment. *BMJ*, 311, 1241–1242.
8 Melnik B (2006). Disturbances of antimicrobial lipids in atopic dermatitis. *Journal der Deutschen Dermatologischen Gesellschaft*, 2, 114–123.
9 Baker BS (2006). The role of microorgamisms in atopic dermatitis. *Clin Exp Dermatol*, 144, 1–9.
10 Leyden JJ, Marples RR and Kligman AM (1974). Staphylococcus aureus in the lesions of atopic dermatitis. *Br J Dermatol*, 90, 525–530.
11 Aly R, Maibach HI and Shinefield HR (1977). Microbial flora of atopic dermatitis. *Arch Dermatol*, 113, 780–782.
12 Roll A, Cozzio A, Fischer B and Schmid-Grendelmeier P (2004). Microbial colonization and atopic dermatitis. *Curr Opin Allergy Clin Immuunol*, 4, 373–378.
13 Stinco G, Piccirillo F and Valent F (2008). A randomized double-blind study to investigate the clinical efficacy of adding a non-migrating antimicrobial to a special silk fabric in the treatment of atopic dermatitis. *Dermatology*, 217, 191–195.
14 Savolainen J, Lammintausta K, Kalimo K and Vlander M (1993). Candida albicans and atopic dermatitis. *Clin Exp Allergy*, 23, 332–339.
15 Brehler RB and Luger TA (2001). Atopic dermatitis: the role of Pityrosporum ovale. *J Eur Acad Dermatol Venereol*, 15, 5–6.
16 Rieg S, Steffen H, Seeber S, Humeny A, Kalbacher H, *et al*. (2005). Deficiency of dermicidin-derived antimicrobial peptides in sweat of patients with atopic dermatitis correlates with an impaired innate defense of human skin in vivo. *J Immunol*, 174, 8003–8010.
17 Ong PY, Ohtake T, Brandt C, Strickland I, Boguniewicz M, *et al*. (2002). Endogenous antimicrobial peptides and skin infections in atopic dermatitis. *N Engl J Med*, 347, 1151–1160.
18 Nomura I, Goleva E, Howell MD, Hamid QA, Ong PY, *et al*. (2003). Cytokine milieu of atopic dermatitis, as compared to psoriasis, skin prevents induction of innate immune response genes. *J Immunol*, 171, 3262–3269.
19 Hinz T, Staudacher A and Bieber T (2006). Neues in der Pathophysiologie der atopischen Dermatitis. *Hautarzt*, 57, 567–575.
20 Sator PG, Schmidt JB and Honigsmann H (2003). Comparison of epidermal hydration and skin surface lipids in healthy individuals and in patients with atopic dermatitis. *J Am Acad Dermatol*, 48, 352–358.
21 Arikawa J, Ishibashi M, Kawashima M, Takagi Y and Ichikawa G (2002). Decreased levels of sphingosine, a natural antimicrobial agent, may be associated with vulnerability of the stratum corneum from patients with atopic dermatitis to colonization by Staphylococcus aureus. *J Invest Dermatol*, 119, 433–439.
22 Rippke F, Schreiner V, Doering T and Maibach HI (2004). Stratum corneum pH in atopic dermatitis: impact on skin barrier function and colonization with Staphylocoocus aureus. *Am J Clin Dermatol*, 5, 217–223.

© Woodhead Publishing Limited, 2011

23 Vasilopoulos Y, Cork MJ, Murphy R, Williams HC, Robinson DA, *et al*. (2004). Genetic association between an AACC insertion in the 3'UTR of the stratum corneum chymotryptic enzyme gene and atopic dermatitis. *J Invest Dermatol*, 123, 62–66.
24 Bendsoe N, Bjornberg A and Asnes H (1987). Itching from wool fibers in atopic dermatitis. *Contact Dermatitis*, 17, 21–22.
25 Hatch KL and Maibach HI (1985). Textile fiber dermatitis. *Contact Dermatitis*, 12, 1–11.
26 Diepgen TL, Stabler A and Hornstein OP (1990). Textile intolerance in atopic eczema – a controlled clinical study. *Z Hautkr*, 65, 907–910.
27 Fischer S, Ring J and Abeck D (2003). Atopisches Ekzem. *Hautarzt*, 54, 914–924.
28 Garnsworthy RK, Gully RL, Kenins P, Mayfield RJ and Westerman RA (1988). Identification of the physical stimulus and the neural basis of fabric-evoked prickle. *J Neurophysiol*, 59, 1083–1097.
29 Senti G, Stainmann LS, Fischer B, Kurmann R, Storni T, *et al*. (2006). Antimicrobial silk clothing in the treatment of atopic dermatitis proves comparable to topical corticosteroid treatment. *Dermatology*, 213, 228–233.
30 Stana-Kleinschek K, Ribitsch V, Kreze T and Fras L (2002). Determination of the adsorption character of cellulose fibers using surface tension and surface charge. *Mat Res Innovat*, 6, 13–18.
31 Rosenau T, Potthast A, Sixta H and Kosma P (2001). The chemistry of side reactions and byproduct formation in the system NMMO/cellulose (Lyocell process). *Prog Polym Sci*, 26, 1763–1837.
32 Kreze T, Jeler S and Strnad S (2002). Correlation between structure characteristics and adsorption properties of regenerated cellulose fibers. *Mat Res Innovat*, 5, 277–283.
33 Adorjan I, Potthast A, Rosenau T, Sixta H and Kosma P (2005). Discoloration of cellulose solutions in N-methylmorpholine-N-oxide (Lyocell). Part 1: Studies on model compounds and pulps. *Cellulose*, 12, 51–57.
34 Zikeli S and Ecker F (2000). Method for spinning a spinning solution and spinning head. Patent WO 01/81663. 2000.
35 Zikeli S and Ecker F (2000). Verfahren und Vorrichtung zur Herstellung von endlosformkörüern. Patent DE10037923. 2000.
36 Meister G and Wechsler M (1998). Biodegradation of N-methylmorpholine-N-oxide. *Biodegradation*, 9, 91–102.
37 Lenz J, Schurz J and Wrentschur E (1992). Comparative characterization of solvent spun cellulose and high wet modulus viscose fibres by their long periods. *Acta Polymer*, 43, 307–312.
38 Eibl M, Eichinger D and Lotz C (1997). Lyocell – The cellulose fibre chameleon. *Lenz Ber*, 76, 89–91.
39 Vorbach D and Taeger E (1998). Eigenschaften von kohlegefüllten Cellulosefasern. *Techn Text*, 41, 67–70.
40 Vorbach D, Schulze T and Taeger E (1998). Keramische Hohlmembranen, Filamente und Strukturstoffe auf Basis des ALCERU-Verfahrens. *Techn Text*, 41, 188–193.
41 Dorhn W, Büttner R and Knobelsdorf C (2002). Superabsorb – a new high absorption Lyocell fiber. *Chem Fibres Int*, 52, 52–55.
42 Zikeli S (2001). Lyocell fibers with health-promoting effect through incorporation of seaweed. *Chem Fibers Int*, 51, 272–276.
43 Hipler UC, Elsner P and Fluhr JW (2006). A new silver-loaded cellulosic fiber with antifungal and antibacterial properties. In: *Biofunctional Textiles and the Skin*. Burg G (ed.). *Curr Probl Dermatol*, Karger, Basel, 33, 165–178.

© Woodhead Publishing Limited, 2011

44 Hipler UC, Elsner P and Fluhr JW (2006). Antifungal and antibacterial properties of a silver-loaded cellulosic fiber. *J Biomed Mater Res Part B: Appl Biomater*, 77B, 156–163.
45 Zhou D, Zhang L, Zhou J and Guo S (2004). Cellulose/chitin beads for adsorption of heavy metals in aqueous solutions. *Water Res*, 38, 2643–2650.
46 Leusch A, Holan ZR and Volesky B (1995). Biosorption of heavy metals by chemically-reinforced biomass of marine algae. *J Chem Technol Biotechnol*, 62, 279–288.
47 Gauger A, Mempel M, Schekatz, Schäfer T, Ring J and Abeck D (2003). Silver-coated textiles reduce Staphyloccous aureus-colonization in patients with atopic eczema. *Dermatology*, 207, 15–21.
48 Fluhr JW, Kowatzki D, Bauer A, Elsner P and Hipler UC (2005). Silberaktivierte Cellulosefasern mit bakterizider und fungizider Wirkung in vitro und in vivo bei Patienten mit atopischer Dermatitis. 5th World Textile Conference AUTEX 2005. 27–29 June 2005 in Portoroz, Slovenia.
49 Warriner R and Burrell R (2005). Infection and the chronic wound: a focus on silver. *Adv Skin Wound Care*, 18(Suppl 1), 2–12.
50 Percival SL, Bowler PG and Russel D (2005). Bacterial resistance to silver in wound care. *J Hosp Infect*, 60, 1–7.
51 Burrell RE (2003). A scientific perspective on the use of topical silver preparations. *Ostomy Wound Management*, 49(5A Suppl), 19–24.
52 Ip M, Lui SL, Poon VKM, Lung I and Burd A (2006). Antimicrobial activities of silver dressings: an in vitro comparison. *J Med Microbiol*, 55, 59–63.
53 Wiegand C, Heinze T and Hipler UC (2009). Comparative in vitro study on cytotoxicity, antimicrobial activity and binding capacity for pathophysiological factors in chronic wounds of alginate and silver-containing alginate. *Wound Rep Reg*, 17(4), 511–521.
54 Lansdown AB (2002). Silver I: Its antibacterial properties and mechanism of action. *J Wound Care*, 11, 125–130.
55 Mundy GR and Guise TA (1999). Hormonal control of calcium homeostasis. *Clin Chem*, 45, 1347–1352.
56 Werfel T, Aberer W, Augustin M, Biedermann T, Fölster-Holst R, *et al*. (2009). Neurodermitis S2-Leitlinie. *JDDG*, (Suppl 1), S1–S46.
57 Gauger A, Fischer S, Mempel M, Schaefer T, Foelster-Holst R, *et al*., (2006). Efficacy and functionality of silver-coated textiles in patients with atopic eczema. *J Eur Acad Dermatol Venereol*, 18, 534–541.
58 Iyer S and Jones DH (2004). Community-acquired methicillin-resistant Staphylococcus aureus skin infection: A retrospective analysis of clinical presentation and treatment of a local outbreak. *J Am Acad Dermatol*, 50, 854–858.
59 Dissemond J, Körber A, Lehnen M and Grabbe S (2005). Methicillin-resistant Staphylococcus aureus (MRSA) in chronic wounds: Therapeutic options and perspectives. *JDDG*, 3, 256–262.
60 Salgado CD, Farr BM and Calfee DP (2003). Community-aquired methicillin-resistant Staphylococcus aureus: a meta-analysis of prevalence and risk factors. *Clin Infect Dis*, 36, 131–139.
61 Briganti S and Picardo M (2003). Antioxidant activity, lipid peroxidation and skin diseases. What's new. *JEADV*, 17, 663–669.
62 Sezer E, Ozugurlu F, Ozyurt H, Sahin S and Etikan I (2007). Lipid peroxidation and antioxidant status in lichen planus. *Clin Exp Dermatol*, 32, 430–434.
63 Hoffmann K (2002). Defined UV protection by apparel textiles. *Arch Dermatol*, 137, 1089–1094.

© Woodhead Publishing Limited, 2011

64 Lymberis A and Olsson S (2003). Intelligent biomedical clothing for personal health and disease management: state of the art and future vision. *Telemed J E Health*, 9, 379–386.
65 Tröster G, Kirstein T and Lukowicz P (2005). *Stud Health Technol Inform*, 117, 63–71.
66 Axisa F, Schmitt PM, Gehin C, Delhomme G, McAdams E and Dittmar A (2005). Flexible technologies and smart clothing for citizen medicine, home healthcare, and disease prevention. *IEEE Trans Info Technol Biomed*, 9, 325–336.
67 El Ghoul Y, Blanchemain N, Laurent T, Campagne C, El Achari A, *et al*. (2008). Chemical, biological and microbiological evaluation of cyclodextrin finished polyamide inguinal meshes. *Acta Biomat*, 4, 1392–1400.
68 Zilberman M and Kraitzer A (2008). Paclitaxel-eluting composite fibers: drug release and tensile mechanical properties. *J Biomed Mater Res A*, 84, 313–323.

© Woodhead Publishing Limited, 2011

13

Infection prevention and control and the role of medical textiles

R. JAMES, University of Nottingham, UK

Abstract: This chapter discusses the importance of *Clostridium difficile* and methicillin-resistant *Staphylococcus aureus* (MRSA) in healthcare-associated infections (HAIs). The chapter reviews the significance of HAI and the principles of infection prevention and control that are used to try to reduce the scale of the problem. The chapter then considers the role of textiles in preventing infection and considers future challenges such as emerging infections that are a threat to healthcare systems worldwide.

Key words: *Clostridium difficile*, healthcare-associated infections (HAIs), infection prevention and control, methicillin-resistant *Staphylococcus aureus* (MRSA), superbugs.

Note: This chapter is adapted from Chapter 6 'Micro-organisms, infection and the role of textiles' by R. James, also published in *Textiles for Hygiene and Infection Control*, ed. B. J. McCarthy, Woodhead Publishing Limited. Published 2011, ISBN: 978-1-84569-636-8.

13.1 Introduction

Infections are caused by pathogenic microorganisms that are capable of invading the body of a human, where they then replicate and cause tissue damage. The human body is colonised (in which case the microorganisms are not causing tissue damage) on the skin and mucosal surfaces by microorganisms that constitute the 'normal flora' of the body. It is estimated that the 10^{13} human cells that make up a human body coexist to form a complex ecosystem with the 10^{14} microbial cells that colonise our skin, mouth and throat, bowel and urinogenital tract. These microbial cells can provide benefit to the human host by, for example, producing antimicrobial compounds that inhibit the growth of pathogens, or by denying an ecological niche in the body to pathogens. Humans have a number of additional defences against microbial infection whose main aim is to prevent access to the normally sterile, deeper tissues that lie below the skin and mucous membranes. These can be divided into constitutive defences which are always activated (innate immunity), and inducible defences which are switched on by the presence of an invading microbe (adaptive immunity). In this chapter we will investigate how infections are spread in hospitals, the principles of infection prevention and control in hospitals and the role that textiles may have in reducing infections.

© Woodhead Publishing Limited, 2011

13.1.1 Historical examples of serious infections

Plague is an infectious disease caused by the bacteria *Yersinia pestis* that has a high fatality rate without treatment. Plague infections have occurred in three pandemics since the sixth century, the first of which was the 'plague of Justinian', which was named after the Roman Emperor and started around AD 532 in Africa and then spread, reaching Constantinople in AD 541 and then Italy, France and Germany. The outbreak in Constantinople is described in detail by Procopius of Caesarea in records that have survived to this day (Zietz and Dunkelberg, 2004).

At that time, the medical explanation for epidemics such as plague was contributed by Hippocrates and Galen and was based on the theory of miasmatic fouling of the air by putrid exhalations from swamps or the victims of plague. We now know that bubonic plague presents in humans in several distinct ways, with bubonic plague and primary pneumonic plague being the most important (WHO, 2002). Bubonic plague is characterised by the swelling of lymph nodes (buboes), and results from the transfer of *Yersinia pestis* by a flea bite or direct contact of a skin lesion with infected material. Primary pneumonic plague is the form with the highest mortality rate and is spread by person to person transmission. This occurs by direct inhalation of droplets containing the pathogen that are spread by coughing and requires being in close proximity to an infected patient (Perry and Fetherston, 1997).

The second plague pandemic started around 1332 and rapidly spread around the world and became known as the Black Death. It is estimated that this plague pandemic killed between 15 and 23.5 million Europeans, or 25% to 33% of the entire population. Many cities introduced quarantine measures, based upon the 40 day restriction on travel imposed in Marseille in 1384. The second plague pandemic continued sporadically until the early eighteenth century with major outbreaks occurring regularly. The most famous in the UK started in London in 1665 and the London Bill of that year records 68 596 out of a total of 97 306 deaths were caused by plague; amounting to between 15% and 20% of the population of the city. Interestingly, some towns such as Bristol, which acted promptly to prevent anyone from London from entering, only had a few cases.

In 1674 the development of a higher magnification microscope by Antoni van Leeuwenhoek resulted in the first observation of bacteria. It was over a hundred years later that Louis Pasteur demonstrated that the contamination of beer is due to airborne microorganisms, and in the same year Robert Koch identified *Bacillus anthracis* as the causative agent of anthrax. The causative agent of plague was identified during the third pandemic, which originated in China around 1855 and reached Hong Kong in 1894, from where it spread to all continents. France sent the bacteriologist Alexandre Yersin to Hong Kong where, in 1894, he succeeded in identifying the causative organism (which, after several name changes, was called *Yersinia pestis* in 1970). Several researchers have questioned whether *Yersinia pestis* was actually the causative organism of the Black Death. This

© Woodhead Publishing Limited, 2011

question has been unambiguously resolved by using the polymerase chain reaction method to amplify *Yersinia pestis* DNA from the dental pulp of teeth extracted from the skeletons of three Black Death victims that were excavated from the same grave in Montpellier, France (Raoult *et al*., 2000).

The rapid discovery of this and many other pathogenic microorganisms in the following years resulted in a firm foundation for the new science of medical bacteriology and an increased understanding of the nature of infection.

13.1.2 Man fights back: antibiotics

In the seventeenth century it was known that natural products were effective in minimising the symptoms of certain protozoal diseases. The bark of the cinchona tree, which contains quinine, was effective against malaria, whilst emetine obtained from the ipecacuanha root was effective against amoebic dysentery. There were however very few options for the treatment of bacterial infections, although mercury had been used to treat syphilis since the sixteenth century; thus explaining the warning to men 'One night with Venus, a lifetime with Mercury'. Similarly, chaulmoogra oil has been used for centuries in India for the treatment of leprosy. Once the agents of infectious disease were identified by Pasteur, Koch and Yersin then began the search for specific antimicrobial drugs that was led by Paul Ehrlich.

Ehrlich realised that, since the protozoa that cause malaria or African sleeping sickness could be distinguished from the host tissues of infected patients by staining with dyes, there may be compounds that exhibited high affinity for the parasite that could be the basis for selective toxicity. Ehrlich began by studying methylene blue and trypan red without any success and then switched his attention to arsenicals, after research in the Liverpool School of Tropical Medicine revealed that atoxyl, an arsenical, protected mice from trypanosomal infection. Ehrlich and his chemist, Bertheim, began trying to synthesise less toxic arsenical derivatives and in 1909 showed that their compound number 606 cured rabbits infected with the spirochaete that causes syphilis. This compound, marketed as Salvarsan, was the first effective antibacterial agent with an acceptable level of toxicity, although it had a limited spectrum of activity. A more soluble derivative, Neosalvarsan, was discovered by Ehrlich in 1912.

The German dyestuff industry started to take an interest in antimicrobial compounds and a derivative of trypan blue was developed by Bayer and marketed in 1924 for the treatment of parasitic diseases. This success spurred research into antimicrobials that resulted in the discovery of the first broad-spectrum antibacterial agents, the sulfonamides at Bayer in 1932 by Gerhard Domagk, for which he won the Nobel Prize in 1939 and became the subject of a Hollywood movie called 'Dr Ehrlich's Magic Bullet' made in 1940. The discovery came from work with Prontosil Rubrum, a compound in which a sulfonamide group was linked to a red dye to aid binding to bacterial cells. Unfortunately, the active

© Woodhead Publishing Limited, 2011

ingredient in Prontosil Rubrum was sulfanilamide, a compound which was already in the public domain so that Bayer was unable to patent it and obtain exclusive rights to its marketing.

As a result, many other companies began to manufacture and market sulfanilamide. The S.E. Massengill Company in Tennessee developed a liquid form by dissolving sulfanilamide in diethylene glycol. At that time it was not necessary to carry out toxicity testing on new drugs in the USA which, had it been carried out, would have revealed that diethylene glycol is a poison (Wax, 1995). The death of more than 100 people after being prescribed 'Elixir Sulphanilamide' in 1937 led to the enactment of the Federal Food, Drug, and Cosmetic Act, which remains the basis for the USA Food and Drug Administration regulation of these products today and undoubtedly saved the USA from the thalidomide tragedy of the early 1960s (Ballentine, 1981). On a more positive note for medicine, the patent position of sulfanilamide was the driver behind the intensive research for derivatives that could be patented, of which May and Baker 693 was the most potent and broad spectrum. It was revealed later that this drug had saved the life of Winston Churchill during World War II when he contracted pneumonia.

The discovery of penicillin by Sir Alexander Fleming in London in 1928 has been suggested to be one of the most important events in medicine. Fleming began his medical studies at St Mary's Hospital Medical School in 1901. He was offered a position in the Inoculation Department at St Mary's in 1906 where the research group led by Almroth Wright aimed to develop vaccines against bacterial infections. During the next eight years Fleming was introduced to bacteriology and vaccine preparation and was involved in the clinical trials of Salvarsan, before Wright and his research group were sent to France to study methods to treat infections in the wounds of injured soldiers during World War I. The high mortality rate caused in soldiers by bacterial infections influenced the research interests of Fleming when he returned to St Mary's at the end of the war. His discovery that nasal mucous and tears contained lysozyme, an antibacterial agent that was effective against some pathogenic strains of streptococci and staphylococci, undoubtedly prepared him for the serendipitous discovery of penicillin in 1928.

Several researchers have tried to duplicate the events of that summer when, on his return from holiday, Fleming observed that an agar plate that he had inoculated with a pathogenic strain of staphylococcus and then left on the laboratory bench had become contaminated with a penicillium mould that inhibited the growth of the bacterial colonies (Bentley, 2005; Hare, 1982). Further experiments quickly determined the best temperature to grow the mould and how to obtain a 'mould juice' extract that contained the antibiotic agent, which he termed penicillin. It was to be ten years later that work by Howard Florey and Ernst Chain in Oxford would solve the problem of obtaining sufficient quantities of the new drug that allowed the successful testing of its antibacterial properties in mice infected with a lethal dose of streptococci in 1940. Production was scaled up in Oxford to obtain the even larger amounts of penicillin required for a clinical trial in patients,

© Woodhead Publishing Limited, 2011

although perhaps surprisingly by this time a decision had been taken not to patent this new drug, as desired by Chain, who was informed by the Medical Research Council that 'the patenting of drugs was unethical and contrary to the traditions of medical research in Britain' (Bentley, 2009). Florey travelled to the USA to enlist their help with increasing the availability of penicillin. Improvements in fermentation technology soon resulted. After the citizens of Peoria were encouraged to send in mouldy food for analysis, the isolation of a high yielding strain from a cantaloupe further enhanced the yield of penicillin (Scoutaris, 1996). Entry into the war after the Japanese attack at Pearl Harbor led to the deployment of enormous resources of money and manpower in the USA in order to further increase production in order to be able to treat wounded soldiers at the battlefront and enable them to survive their wounds and fight again and thus gain a military advantage.

In the UK, in 1942 Florey donated enough penicillin to enable Fleming to save the life of a family friend with meningitis. As a result Fleming persuaded the UK government to scale up the production of penicillin in this country with the help of the pharmaceutical companies. It was fitting in 1945 when Fleming, Florey and Chain were jointly awarded the Nobel Prize for the discovery of penicillin. It can be argued that Norman Heatley, a biochemist in Oxford who made outstanding contributions to solving the problem of purifying penicillin from crude extracts also deserved recognition.

The structure of the penicillin molecule was solved in 1945 and revealed the presence of an unusual four-membered beta-lactam ring that subsequently gave rise to the name of the family of antibiotics that included penicillin, the beta-lactams. The identification of a critical building block in the synthesis of penicillin that could be modified by chemical synthesis resulted in the development of a large number of 'semi-synthetic penicillins' in the 1960s. The discovery in Oxford of the same beta-lactam ring structure in cephalosporin C, an antibiotic first discovered in Italy in 1945 by Brotzu (Hamilton-Miller, 2000), this time resulted in UK patents that generated millions of pounds of licence income from the subsequent development of semi-synthetic cephalosporin derivatives. That beta-lactam antibiotics still constitute one of our most important weapons against bacterial infections is a testament to the importance of the discovery of penicillin.

The discovery of sulfonamide and the widespread clinical use of penicillin during World War II marked the beginning of the 'golden age of antibiotic discovery' that lasted until the 1960s. Selman Waksman at Rutgers University carried out an extensive investigation of the ability of microorganisms in soil to inhibit pathogenic bacteria that resulted in the discovery of streptomycin in 1943. This was the first antibiotic with activity against *Mycobacterium tuberculosis*, the causative agent of TB which affects about one third of the world's population. Rifampicin was also found to be produced by a soil microorganism. During this period many of the major classes of antibiotic that are still in use today were discovered.

© Woodhead Publishing Limited, 2011

13.1.3 Bacteria fight back: antibiotic resistance mechanisms

Fleming observed in his early laboratory experiments that he could isolate resistant colonies of bacteria that had been treated with penicillin. He sounded a very prescient note of warning in his Nobel Lecture on the potential risk of underdosing when treating a streptococcal infection and how this could 'educate them to resist penicillin' (Fleming, 1945). However, the rate of discovery of a large number of antibiotics that were effective in treating infections caused by bacterial pathogens seems to have generated a misplaced complacency such that, in 1967, the USA Surgeon General, William H. Stewart, told a group of health officers in the White House 'that it was time to close the book on infectious diseases and shift all national attention (and dollars) to [what he termed] the New Dimensions of health: chronic diseases'. It is now apparent that neither Fleming nor Stewart appreciated the ingenuity and sheer variety of the ways in which bacterial pathogens would become resistant to antibiotics. In many ways exposure of growing bacterial cells to an antibiotic is an extreme example of Charles Darwin's 'survival of the fittest' theory of natural selection as only the bacterial cells that have in some way developed resistance will survive to reproduce and thus pass on their resistance to future generations.

There are four major antibiotic resistance mechanisms:

- Antibiotic inactivation
- Altered antibiotic target or overproduction of antibiotic target
- Reduced antibiotic accumulation
- Bypass antibiotic-sensitive step.

Resistance against a class of antibiotics, such as the beta-lactams, can result from more than one of these four mechanisms (Table 13.1).

There are two types of antibiotic resistance in clinical isolates: *intrinsic resistance*, which is an intrinsic property of a bacterial species that makes them resistant to an antibiotic, and *acquired resistance* where a population of bacteria that were initially sensitive to an antibiotic become resistant. Acquired resistance can be due to the acquisition of mutations in the gene that encodes the cellular target of the antibiotic that for example reduces antibiotic binding, or by the acquisition of a plasmid that encodes a resistance gene. Intrinsic resistance, since

Table 13.1 Antibiotic resistance mechanisms

Inactivation	Altered target	Reduced accumulation	Bypass target
Aminoglycosides	Beta-lactams	Aminoglycosides	Trimethoprim
Beta-lactams	Chloramphenicol	Beta-lactams	Sulfonamides
Chloramphenicol	Quinolones	Chloramphenicol	
	Rifampicin	Quinolones	
	Streptomycin	Tetracyclines	

© Woodhead Publishing Limited, 2011

it is predictable, is by far the easiest to overcome, however acquired resistance is a serious threat to the continued existence of many antibiotic treatments.

Plasmids are extra-chromosomal genetic elements that replicate independently of the bacterial circular genome and can be transferred from cell to cell by the process of bacterial conjugation. Plasmids frequently carry several different antibiotic resistance genes that are transferred en bloc during plasmid transfer, with the result that the recipient bacterial cell that acquires the plasmid will become resistant to several classes of antibiotic simultaneously. It is obvious that the transfer of these resistance-encoding plasmids, or R-plasmids, to bacterial pathogens will significantly reduce the available therapeutic options to treat an infected patient.

The mobilisation of antibiotic resistance genes between plasmids and/or the bacterial genome is mediated by 'transposons' which are mobile DNA sequences, that are often termed 'jumping genes' that can transpose from one DNA molecule to another in a replicative process that results in the transposon being present in both DNA molecules. Since the central region of a transposon often carries antibiotic resistance gene(s), it is easy to appreciate how a newly developed resistance gene can be rapidly spread between different R-plasmids and thus be mobilised into a wide variety of bacterial pathogens. This has led to the concept of the 'antibacterial resistome', which effectively is made up of the whole microbial world together with its complement of R-plasmids and transposons. A resistance gene that has been developed in any microorganism can be mobilised to any bacterial pathogen which is exposed to the formidable selective pressure of antibiotic therapy. It is perhaps amazing that some antibiotic resistance mechanisms are inducible and are only switched on in the host bacterial cell in the presence of the antibiotic, with the effect that they save energy for the cell by producing the resistance gene products only when they are required.

13.2 Superbugs and healthcare-associated infections (HAIs)

With the realisation that hospitals are populated both by 'sick patients', with underlying medical conditions that may make them more susceptible to infection, and by 'fit bacteria' that are capable of causing serious infections and often carry antibiotic resistance genes, it is easy to see why the UK is confronted with a serious problem of healthcare-associated infections (HAIs) caused by 'superbugs'. This term appeared in newspapers in the UK in 1985 in the context of stories about the agricultural use of antibiotics leading to the evolution of antibiotic-resistant pathogenic bacteria. From about 1997 the term began to be used widely both in broadsheet newspapers and by politicians in stories concerning methicillin-resistant *Staphylococcus aureus* (MRSA). The use of the term 'superbugs' implies that there are ordinary 'bugs' which, although capable of causing infections, are not a threat, and then there are superbugs, like *Clostridium difficile* (*C. difficile*)

© Woodhead Publishing Limited, 2011

and MRSA, that are ubiquitous in healthcare settings such as hospitals, threatening and unconquerable (Washer and Joffe, 2006; Nerlich, 2009). The accepted definition of an HAI today is:

> An infection that occurs more than 48 hours after admission to hospital; or an infection that occurs within 10 days of discharge from hospital (within 30 days for a surgical wound infection); or an infection that occurs within 72 hours of an out-patient procedure.

Prior to the introduction of antibiotics the mortality rate of individuals with a *Staphylococcus aureus* (*S. aureus*) infection was 80%. In 1942, two years after the introduction of penicillin, the first penicillin-resistant *S. aureus* isolate was observed in a hospital patient. The first MRSA strain was reported in the UK in 1961 after the introduction of methicillin in 1959 to counter the emergence of the penicillin-resistant *S. aureus* strains (Barber, 1961). The strain was observed to spread rapidly and caused outbreaks of infections, especially amongst children, and a small number of deaths (Stewart and Holt, 1963). MRSA strains were subsequently isolated in a number of countries and the first serious outbreaks were observed in eastern Australia in the 1970s. A dramatic increase in the number of MRSA bacteraemias began in the UK in the early 1990s.

MRSA strains result from the acquisition by methicillin-sensitive *S. aureus* (MSSA) strains of the *mecA* gene that encodes a modified penicillin-binding-protein that confers resistance to all beta-lactam antibiotics. The *mecA* gene is found in all MRSA strains as part of a staphylococcal cassette chromosome (*SCCmec*) element that inserts into the *S. aureus* genome at the same specific site. *SCCmec* elements can be grouped into one of eight types (*SCCmec* type I to *SCCmec* type VIII) based upon their genetic composition. This is indicative that the evolution of MRSA strains from MSSA has happened independently a number of times. Several of the *SCCmec* types carry resistance genes against other classes of antibiotics in addition to the beta-lactams. This has significant implications in reducing the therapeutic options available to clinicians and explains the widespread use of vancomycin to treat patients diagnosed with an MRSA infection. The identification of nine MRSA isolates in the USA that exhibit resistance to high concentrations of vancomycin, together with the general increase in the vancomycin concentration required to kill many MRSA isolates, are worrying developments for the continued effectiveness of this antibiotic.

S. aureus colonises many sites on the human body without causing an infection. Some 30% of the population are found to carry *S. aureus* at any one time, principally in the nose. Twenty per cent of the population always seem to be colonised whilst one third are only transiently colonised. A significant percentage of the population are thus never colonised with *S. aureus* but the reasons for this are not entirely clear (Wertheim *et al*., 2005). The MRSA colonisation rate is significantly lower at between 1 and 10%, depending on patient age and degree of previous exposure to healthcare settings, but again some individuals always seem to be colonised.

© Woodhead Publishing Limited, 2011

C. difficile is found in the gastrointestinal tract of two to three per cent of healthy adults without causing any clinical symptoms. *C. difficile*, unlike *S. aureus*, can exist as either vegetative, growing bacterial cells or as dormant, heat-resistant spores. The latter are an important route of transmission from one patient to another. Antibiotic therapy, particularly of elderly patients in hospitals, allows *C. difficile* to proliferate in the gastrointestinal tract by removing some of the competing microorganisms and cause an infection that can range from mild diarrhoea to life-threatening pseudomembranous colitis. Patients with a *C. difficile* infection (CDI) are treated with one of two antibiotics, metronidazole or vancomycin. In a significant percentage of treated patients the CDI recurs, often several times, and results in significant mortality.

13.2.1 The scale of the HAI problem

The number of MRSA bacteraemia reports in England together with the number of death certificates that either mention MRSA, or list MRSA as the cause of death, are shown for 2001–2008 in Table 13.2. The number of CDI cases dramatically increased in England between 1990 and 2004. Nearly 50 000 cases were reported in 2007 with 20% of them being in younger age groups previously not considered to be high risk. The number of CDI cases in England together with the number of death certificates that either mention *C. difficile* or list *C. difficile* as the cause of death are shown for 2004–2008 in Table 13.3.

An important factor in the increase of CDI cases was the appearance of a more virulent strain *C. difficile* 027 which produces more toxins and is associated with more severe disease, increased risk of relapse and higher mortality. This strain was involved in two big outbreaks in England at Stoke Mandeville in 2003–2005 (Caldwell, 2006) and at Maidstone & Tunbridge Wells NHS Trust in 2005–2006 that led to a large number of deaths. The latter outbreak was investigated in a BBC TV Panorama programme that I was pleased to be significantly involved with.

Table 13.2 Number of MRSA bacteraemia cases and deaths in England

Year	Bacteraemia	Death certificate	
		Mentions MRSA	MRSA listed as cause of death
2001	7291	731	258
2002	7426	794	246
2003	7700	968	322
2004	7233	1069	334
2005	7096	1536	432
2006	6383	1556	580
2007	4451	1517	439
2008	2935	1137	200

© Woodhead Publishing Limited, 2011

Table 13.3 Number of *C. difficile* infections and deaths in England

Year	CDI	Death certificate	
		Mentions CDI	CDI listed as cause of death
2004	44 314	2238	1229
2005	51 767	3757	2063
2006	55 681	6480	3490
2007	49 785	8324	4056
2008	37 134	5931	2502

The annual cost of HAIs to the NHS in the UK was estimated to be £1 billion by the National Audit Office (Bourn, 2000). 1.7 million people per year develop an HAI in the USA, resulting in 100 000 deaths (Klevens *et al*., 2007), at an annual cost to the healthcare system of between $28.4 and $45 billion (in 2007 dollars) (Scott, 2009). Assuming that 20% of the HAIs in the USA are preventable, the annual benefits of prevention range from $5.7 to $6.8 billion; whilst if we assume that 70% of HAIs are preventable the annual benefits of prevention are between $25.0 and $31.5 billion.

13.3 Principles and practice of infection prevention and control in hospitals

Ignaz Semmelweis in Vienna was the first to show that infections can be transmitted to susceptible patients within hospitals. Semmelweis carried out a detailed investigation to find out why the two maternity clinics at his hospital had significantly different mortality rates due to puerperal fever. A major difference between the two clinics was that the First Clinic (with significantly higher death rates) was used for the training of medical students, whilst the Second Clinic (with lower death rates) was used for the training of midwives. Following the death in 1847 of a colleague who had received a cut from a student's scalpel during a post-mortem, Semmelweis carried out the autopsy of his friend and noticed similarities in the pathology to that of the mothers who had died of puerperal fever. He proposed that medical students carried 'cadaverous particles' on their hands from the autopsy room to the mothers that they examined in the First Clinic. This explained why the midwives, who were not involved in post-mortem examinations, had much lower death rates in the Second Clinic. As a result, Semmelweis introduced a policy of hand washing in chlorinated lime that resulted in a drastic reduction in death rates in the First Clinic. However, his work was ridiculed by the medical profession as he could not explain his findings and, by implication, his work implied that doctors were the cause of the puerpural fever and subsequent death of the mothers. This

© Woodhead Publishing Limited, 2011

was perhaps the reason why he was eventually committed to an asylum in 1865 and died 14 days later of septicaemia. It was some 20 years later, when Louis Pasteur developed the germ theory of disease, that Semmelweis was vindicated.

Infection prevention and control as a discipline now uses epidemiological principles and statistical analysis in order to prevent the transmission of infections from one patient to another. The key concepts in preventing infections involve the three links in the chain of infection:

- Potential sources of infection
- The routes of transmission of infection
- The role of host factors (i.e. the patient).

The aim is to utilise this information to *break the chain of transmission* of infection by targeting any or all of the links of the chain.

13.3.1 Sources of infection

Possible sources of infection are patients who are carriers of an infectious organism, such as MRSA in the nose or *C. difficile* in the gastrointestinal tract; or patients who are infected. There are also potential environmental sources such as surfaces in a hospital ward, door handles, or toilets in communal areas used by patients that are contaminated with body fluids; however, there is little evidence to enable a judgement to be made on the relative significance of the hospital environment as a source of infection (Dancer, 2008). Whilst it is possible to show that pathogenic bacteria such as MRSA can be recovered by sampling the hospital environment, it is much more difficult to conclusively demonstrate that these organisms are the source of infections in patients who are in contact with this environment.

13.3.2 Routes of transmission of infection

The routes of transmission by which pathogens can be transferred from the source of infection to the host can be either airborne; by contact; or percutaneous. Airborne transmission involves the spread of infections such as influenza and TB via water droplets. Contact transmission can involve direct person-to-person transmission from the source to a susceptible host (as with MRSA), or can involve contact with body fluids such as faecal material (*C. difficile*), equipment such as endoscopes or food. Percutaneous transmission can occur via insect vectors (malaria); intravascular lines (MRSA); or as a result of sharps injuries (hepatitis B, HIV).

13.3.3 The role of host factors

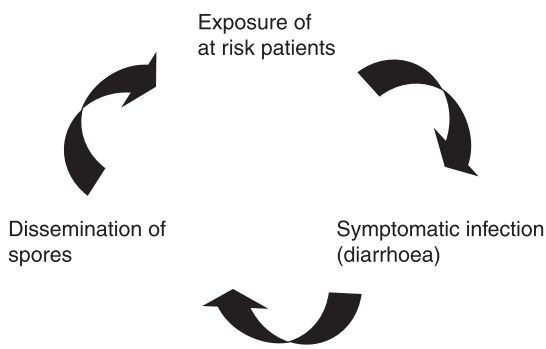
The host is the third link in the chain of infection. Patients in hospital may have a serious underlying medical condition that reduces their normal defences against infection, for example if they are being treated with immunosuppressive drugs to

© Woodhead Publishing Limited, 2011

avoid organ rejection after a transplant. A pathogen such as MRSA may enter the host through breaks in the skin such as a surgical site; via a medical device such as an intravenous catheter; or via the lungs. *C. difficile* is acquired via contact of the host with faecal material containing cells or spores and subsequent entry via the gastrointestinal tract. Patients in intensive care, or having a history of recurrent admissions or prolonged hospital stays, have a higher incidence of HAIs.

13.3.4 Breaking the chain of infection

The chain of infection is vulnerable at each of the three links in the chain. Sources of infection can be minimised by a high standard of cleaning (Dancer, 2008); cleaning and sterilising all surgical equipment; and controlling the standard of food given to patients. The introduction in April 2009 of MRSA screening of all patients admitted to hospitals in England for elective surgery has the potential to identify MRSA carriers on admission to hospital and allow the opportunity for decolonisation treatments. If successful, this policy would be expected to result in a considerable reduction in the potential sources of MRSA infection in English hospitals. Transmission of infections can be blocked by the provision of suitable protective clothing (including medical textiles) for both healthcare workers and patients; observance of the requirements for handwashing, especially by healthcare workers; and the isolation of MRSA carriers, and of *C. difficile* or MRSA-infected patients. Improved host resistance to infection can be achieved by good nutrition; immunisation; minimising the use of invasive medical devices; the appropriate use of antibiotics; and education of both healthcare workers and patients. The chain of infection for *C. difficile* is shown in Fig. 13.1.



13.1 Chain of infection for *C. difficile*. At-risk patients are exposed to *C. difficile* spores after contact with faecal matter contaminating surfaces, door handles, etc., in hospital wards. In those patients where a symptomatic infection results in diarrhoea, more faecal material containing *C. difficile* spores can contaminate the ward again. Preventing infection requires the chain to be broken by, for example, isolating infected patients and enhanced cleaning of the ward.

© Woodhead Publishing Limited, 2011

Under considerable political pressure to reduce the incidence of HAI, many hospitals in England introduced a large number of improvements in their infection control measures from 2004 onwards. Since 2005–2006 there has been a considerable reduction in the number of reported CDIs and MRSA bacteraemias but it is difficult to determine what contribution any individual infection control measure has made to this reduction. It would be very expensive and time consuming to set up a randomised clinical trial to obtain this information.

13.4 The role of textiles in infection prevention and control

The traditional uses for textiles in infection prevention and control are in areas such as bedding, bed curtains, drapes, dressings and uniforms, which will be highlighted in other chapters in this book. There is now considerable interest in the application of nanotechnology in medical textiles. The accepted definition of nanotechnology is 'the application of scientific knowledge to control and utilise matter at the nanoscale (size range 1–100 nm) where size related properties and phenomena can emerge'.

13.4.1 Antimicrobial wound dressings

Silver nanoparticles are widely used in antimicrobial wound dressings because of their recognised antibacterial activity (Tian *et al*., 2007). Wound dressings are manufactured by means of a bi-layer of silver-coated, high-density polyethylene mesh with a rayon adsorptive polyester core that delivers nanocrystalline silver that maintains an effective antimicrobial activity. Nanocrystalline silver dressings have been clinically tested in patients with burns, ulcers and other non-healing wounds and have been very successful in facilitating wound care. Wound dressings have been also developed which combine an electrospun polyurethane nanofibrous membrane and silk fibroin nanofibres. These electrospun materials are characterised by a wide range of pore size distribution, high porosity, and high surface area-to-volume ratio that is important for fluid exudation from the wound, avoiding wound desiccation, and preventing infections by exogenous microorganisms.

13.4.2 Anti-adhesive wound dressings

Textile wound dressings such as plasters or bandages are used to cover wounds until the healing process can protect the wound; however, traditional wound dressings generally adhere to the healing wound, causing a new injury on removal, and thereby interrupting the healing process. Innovative wound dressings with anti-adhesive properties to the healing wound have been obtained by coating the common viscose bandages with silica nanosol modified with long-chain alkyltrialkoxysilanes. An additional, valuable feature of these innovative wound

© Woodhead Publishing Limited, 2011

dressings is their excellent absorption properties of wound exudates that facilitate the healing process especially in bedridden patients with chronic wounds.

13.5 Future challenges

The data indicate that it took some 15 years for UK hospitals to start to get to grips with the problems caused by CDI and MRSA infections. It should be borne in mind that whilst the number of reported MRSA bacteraemias has fallen from a quarterly average of 1925 in 2003–2004 to 482 between January and March 2010, bacteraemias caused by other bacteria such as *Escherichia coli* and *Klebsiella pneumoniae* have increased over the same time period. This implies that the infection control measures that have been successful against MRSA are less effective against other pathogens, which raises clear concerns as healthcare systems face the threat from a range of emerging infections such as *Acinetobacter baumannii* and ESBLs (extended spectrum beta lactamases). In addition, infections with *C. difficile* and MRSA are increasingly being found in the community in patients who have had limited exposure to hospitals.

13.5.1 Emerging infections in hospitals: *Acinetobacter baumannii*

Acinetobacter baumannii (*A. baumannii*) is an example of an opportunistic pathogen which is generally harmless to healthy individuals but can cause serious infections such as ventilator-associated pneumonia, wound infections and bacteraemias in critically ill hospital patients. Wound infections caused by *A. baumannii* have been identified in a significant number of soldiers injured in Iraq after repatriation to the UK or USA (Davis *et al*., 2005). Their resistance to desiccation and disinfectants make it difficult to eliminate *A. baumannii* from the hospital environment. Epidemics of *A. baumannii* in hospital are most commonly triggered by the introduction of a patient who is colonised followed by spread to other patients (Dijkshoorn *et al*., 2007). There is evidence of the spread of epidemic strains of *A. baumannii* between hospitals, presumably due to the transfer of patients. Epidemics in hospitals are usually ended by cleaning and disinfecting wards, which implies that the environment is an important source of *A. baumannii* infection. The bacteria can spread short distances through the air in water droplets or on scales of skin, but the most common route of transmission appears to be person-to-person, via the hands of healthcare workers.

The treatment of *A. baumannii* infections can be complicated by both its intrinsic resistance to many widely used antibiotics, and the acquisition of resistance to many other classes of antibiotic, resulting in multidrug resistant (MDR) strains. Resistance to the carbapenems, such as imipenem, is particularly significant as these antibiotics have been widely used to treat MDR-*A. baumannii* infections. The recent reports of acquired resistance to colistin and tigecycline

© Woodhead Publishing Limited, 2011

implies that the potential of *A. baumannii* strains to develop resistance against all the currently available antibiotics has now been achieved. It is fortunate that such strains are still only opportunistic pathogens as *A. baumannii* is perfectly adapted to maximise its transmission to susceptible patients whilst being able to resist the antibiotics and disinfectants that we use to try to control it (Perez *et al*., 2008).

13.5.2 Emerging infections in hospitals: ESBLs

One reason for the importance of beta-lactam antibiotics has been the success in developing second and third generation antibiotics of this class in response to the widespread appearance of resistance to earlier generations of beta-lactams encoded by beta-lactamase enzymes that cleave the beta-lactam ring and inactivate the antibiotic. The first beta-lactamase enzyme produced by a strain of *Klebsiella pneumonia* that was able to inactivate such 'extended spectrum beta-lactam antibiotics' was described in Germany in 1983 and was soon followed by others. These enzymes were described as extended spectrum beta-lactamases (ESBLs) in 1989 (Philippon *et al*., 1989) and were increasingly isolated during the 1990s in many countries. A new family of ESBLs, the CTX-M enzymes, were first detected in patients in Germany and Argentina but have now become the most prevalent ESBLs worldwide (Canton and Coque, 2006). A large number of CTX-M beta-lactamases have now been identified with the common gastrointestinal tract organism *Escherichia coli* being identified as the most common producing strain. Bacteria such as *Klebsiella pneumonia* and *Escherichia coli* can cause urinary tract infections, pneumonia, bacteraemia and meningitis (Schwaber and Carmeli, 2008).

Based on amino-acid sequence homology, chromosomal beta-lactamase genes in Kluyvera species have been identified as the potential source of many of these CTX-M enzymes. These genes have migrated onto plasmids that can readily be transferred between different bacterial species, hence explaining the rapid spread of these ESBLs. CTX-M-producing isolates are also now being identified increasingly in infections in the community as well as in hospital settings. Some studies have suggested that it is these community strains that have been the source of the large increase in CTX-M infections in hospitals.

ESBL-producing isolates typically display resistance to other classes of antibiotics as well as beta-lactams due to the acquisition of additional antibiotic-resistance genes by these isolates. This reduces the options for treating hospital patients infected with CTX-M isolates to the carbapenems, which have been termed the 'antibiotics of last resort'. The recent appearance of bacteria producing carbapenemases (beta-lactamases that can inactivate carbapenems) means that there is no reliable antibiotic left to treat these infections, with potentially devastating consequences for healthcare systems worldwide (Schwaber and Carmeli, 2008).

© Woodhead Publishing Limited, 2011

13.5.3 Community infections: CA-MRSA

Since the isolation of the first MRSA strain in 1961 various hospital-associated MRSA (HA-MRSA) clones have spread worldwide and were the cause of the majority of hospital-acquired infections (Deurenberg and Stobberingh, 2008). The first report of community-associated MRSA (CA-MRSA) infections was in 1993 in Aboriginal patients living in remote communities in Western Australia, with no contact with hospitals, and caused skin and soft tissue infections. Since then a number of CA-MRSA clones have spread worldwide and have been largely responsible for the increased incidence of MRSA infections, even in countries such as Denmark and Norway who had previously been very successful in preventing the large increase in HA-MRSA infections. The Center for Disease Control and Prevention in the USA defines CA-MRSA as MRSA strains isolated in an outpatient setting, or isolated from patients within 48 hours of hospital admission. Most CA-MRSA strains can also be distinguished by production of Panton–Valentine leucocidin (PVL), a toxin that may have a role in their pathogenicity. The Health Protection Agency in the UK reports a significant increase in the number of PVL-positive strains of *S. aureus* in the UK but suggests that the incidence of CA-MRSA or CA-MSSA is still low compared with many other countries.

CA-MRSA has had a dramatic effect on the treatment of suspected staphylococcal infections in geographical regions where CA-MRSA is prevalent as it is likely that most beta-lactam antibiotics will be ineffective (Chambers and Deleo, 2009). The acquisition by CA-MRSA strains of resistance to other classes of antibiotic will further reduce the therapeutic options for treating these infections. CA-MRSA strains have started to replace HA-MRSA strains in hospitals, especially in the USA and Taiwan. There is evidence that CA-MRSA strains are more virulent and more transmissible by person-to-person contact. The improved infection control policies that have resulted in a significant reduction in MRSA bacteraemias in hospital patients in the UK may be threatened, both by the expected increase in CA-MRSA infections and by the wider range of types of infections that have been observed to cause. At the extreme CA-MRSA can cause necrotising pneumonia with a mortality rate of >50% in less than 72 hours.

13.6 A holistic approach to preventing infections

The increasing incidence of CA-MRSA, CDI and ESBLs in patients in the community suggests that we will have to change our perception of the problem of infection. Serious infections are no longer concentrated in hospitals where facilities for their diagnosis and expertise to advise on their treatment are more readily available. This will have significant implications for the effective delivery of healthcare in the twenty-first century. We will have to develop improved diagnostic tests that can be used closer to the point of care rather than just in

© Woodhead Publishing Limited, 2011

hospital microbiology laboratories so that we have more rapid information on the causative organism to aid treatment. We also need new antibiotics to give more treatment options, especially against infections caused by MDR organisms such as *A. baumannii*, ESBLs and MRSA. Unfortunately, the pace of discovery of new antibiotics has declined dramatically since the 1980s. The reasons for this are complex and involve the difficulty (and hence higher cost) of developing new antibiotics compared with most other types of therapeutic agents; profits will be higher for drugs to treat chronic conditions that have to be taken every day for life, rather than for antibiotics that are only taken for seven days when the patient has an infection; and antibiotics and anticancer agents are the only drugs that have built-in obsolescence due to the development of resistance against their activity. Some interesting ideas to promote the development of new antibiotics are now starting to appear (Vagsholm and Hojgard, 2010), but it would make sense in this connected world in which we live if these could be co-ordinated by bodies such as the WHO, rather than being left to individual nations or pharmaceutical companies.

Infection control measures must be more available in the community, along with better education of the public, in order to prevent the acquisition and prevention of infections. This will open up opportunities for innovative products such as medical textiles for use in the community. Dressings that can detect a wound infection in an elderly person living alone in their own home and then send a wireless signal to a community infection control team may be an example of what will become common in the next decade. This will allow rapid point of care diagnostic tests to be carried out, both to identify the pathogen and detect any antibiotic resistance properties, allowing treatment of the infection to be commenced during a single home visit.

13.7 Sources of further information

Brown K (2004), *Penicillin Man: Alexander Fleming and the antibiotic revolution*, Stroud: Sutton Publishing Limited.

Friedman M and Friedland GW (1998), *Medicine's 10 greatest discoveries*, Yale: Yale University Press, 37–64 and 168–191.

Lax E (2004), *The mould in Dr Florey's coat*, London: Little, Brown.

Mann J (1999), *The Elusive Magic Bullet*, Oxford: Oxford University Press, 1–76.

Walsh C (2003), *Antibiotics: Actions, origins, resistance*, Washington, DC: ASM Press.

13.8 References

Ballentine C (1981). Sulphanilamide Disaster, U.S. Food and Drug Administration. Available: http://www.fda.gov/AboutFDA/WhatWeDo/history/ProductRegulation/Sulfanilamide [Accessed 16 June 2010].

Barber M (1961). Methicillin-resistant staphylococci, *J Clin Pathol*, 14, 385–393.

Bentley R (2005). The development of penicillin: Genesis of a famous antibiotic, *Perspect Biol Med*, 48, 444–452.

© Woodhead Publishing Limited, 2011

Bentley R (2009). Different roads to discovery; Prontosil (hence sulfa drugs) and penicillin (hence beta-lactams), *J Ind Microbiol Biotechnol*, 36, 775–786.

Bourn (2000). Available at: www.nao.org.uk/publications/9900/hospital_acquired_infection.aspx

Caldwell S (2006). HSE investigation into outbreaks of *Clostridium difficile* at Stoke Mandeville Hospital, Buckinghamshire Hospitals NHS Trust. Health & Safety Executive, UK. Available: http://www.hse.gov.uk/healthservices/hospitalinfect/stokemandeville.htm [Accessed 16 June 2010].

Canton R and Coque TM (2006). The CTX-M beta-lactamase pandemic, *Curr Opin Microbiol*, 9, 466–475.

Chambers H F and Deleo FR (2009). Waves of resistance: *Staphylococcus aureus* in the antibiotic era, *Nat Rev Microbiol*, 7, 629–641.

Dancer SJ (2008). Importance of the environment in meticillin-resistant *Staphylococcus aureus* acquisition: the case for hospital cleaning, *Lancet Infect Dis*, 8, 101–113.

Davis KA, Moran KA, McAllister CK and Gray PJ (2005). Multidrug-resistant Acinetobacter extremity infections in soldiers, *Emerg Infect Dis*, 11, 1218–1224.

Deurenberg RH and Stobberingh EE (2008). The evolution of *Staphylococcus aureus*, *Infect Genet Evol*, 8, 747–763.

Dijkshoorn L, Nemec A and Seifert H (2007). An increasing threat in hospitals: multidrug-resistant *Acinetobacter baumannii*, *Nat Rev Microbiol*, 5, 939–951.

Fleming A (1945) Available at: http://nobelprize.org/nobel_prizes/medicine/laureates/1945/fleming-lecture.pdf

Hamilton-Miller JM (2000). Sir Edward Abraham's contribution to the development of the cephalosporins: a reassessment, *Int J Antimicrob Agents*, 15, 179–184.

Hare R (1982). New light on the history of penicillin, *Med Hist*, 26, 1–24.

Klevens RM, Edwards JR, Richards CL, Horan TC, Gaynes RP, *et al*. (2007). Estimating healthcare-associated infections and deaths in U.S. hospitals, 2002, *Public Health Rep*, 122, 160–166.

Nerlich B (2009). 'The post-antibiotic apocalypse' and the 'war on superbugs': catastrophe discourse in microbiology, its rhetorical form and political function, *Public Underst Sci*, 18, 574–588; discussion 588–590.

Perez F, Endimiani A and Bonomo RA (2008). Why are we afraid of *Acinetobacter baumannii*? *Expert Rev Anti Infect Ther*, 6, 269–271.

Perry RD and Fetherston JD (1997). *Yersinia pestis*–etiologic agent of plague, *Clin Microbiol Rev*, 10, 35–66.

Philippon A, Labia R and Jacoby G (1989). Extended-spectrum beta-lactamases, *Antimicrob Agents Chemother*, 33, 1131–1136.

Raoult D, Aboudharam G, Crubezy E, Larrouy G, Ludes B and Drancourt M (2000). Molecular identification by "suicide PCR" of *Yersinia pestis* as the agent of medieval black death, *Proc Natl Acad Sci U. S. A.*, 97, 12800–12803.

Schwaber MJ and Carmeli Y (2008). Carbapenem-resistant Enterobacteriaceae: a potential threat, *JAMA*, 300, 2911–2913.

Scott (2009). Available at: www.cdc.gov/ncidod/dhqp/pdf/Scott_CostPaper.pdf

Scoutaris M (1996). 'Moldy Mary' and the Illinois Fruit and Vegetable Company, *Pharm Hist*, 38, 175–177.

Stewart GT and Holt RJ (1963). Evolution of natural resistance to the newer penicillins, *Br Med J*, 1, 308–311.

Tian *et al*. (2007). Topical delivery of silver nanoparticles promotes wound healing, *ChemMedChem*, 2, 129–136.

© Woodhead Publishing Limited, 2011

Vagsholm I. and Hojgard S (2010). Antimicrobial sensitivity–A natural resource to be protected by a Pigouvian tax? *Prev Vet Med*, 96, 9–18.

Washer P and Joffe H (2006). The 'hospital superbug': social representations of MRSA, *Soc Sci Med*, 63, 2141–2152.

Wax PM (1995). Elixirs, diluents, and the passage of the 1938 Federal Food, Drug and Cosmetic Act, *Ann Intern Med*, 122, 456–461.

Wertheim HF, Melles DC, Vos MC, van Leeuwen W, van Belkum A, *et al*. (2005). The role of nasal carriage in *Staphylococcus aureus* infections, *Lancet Infect Dis*, 5, 751–762.

WHO (2002). www.who.int/topics/plague/en/

Zietz BP and Dunkelberg H (2004). The history of the plague and the research on the causative agent *Yersinia pestis*, *Int J Hyg Environ Health*, 207, 165–178.

© Woodhead Publishing Limited, 2011

14

Absorbent products for personal health care and hygiene

F. WIESEMANN and R. ADAM, Procter & Gamble Service GmbH, Germany

Abstract: Products for baby and adult incontinence and feminine hygiene are important parts of daily life for millions of people around the world. The consumer needs, clinical performance and skin care requirements and technologies used in these products are similar across product categories; therefore, this chapter will cover a range of absorbent products used for personal health care and hygiene. It will explore the needs of patients and consumers, hygiene implications, testing methods, and the application of innovative technologies to products. Finally, we will discuss emerging trends in this field, and provide sources that may be of use to the reader interested in obtaining additional information.

Key words: adult incontinence products, superabsorbent baby diapers, feminine hygiene products, skin health, sustainability.

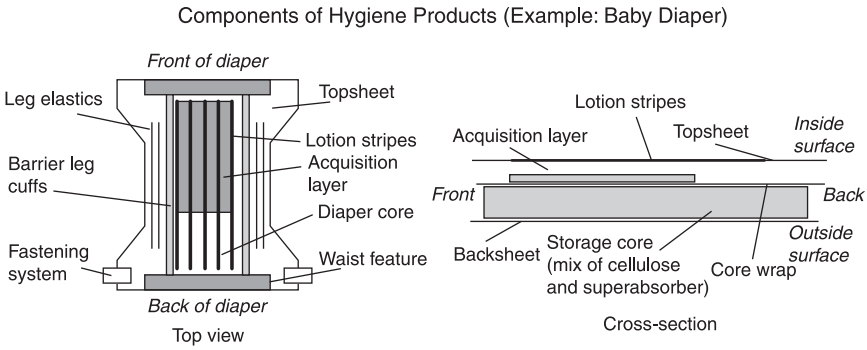
14.1 Introduction

Products for baby and adult incontinence and feminine hygiene are important parts of daily life for millions of people around the world. While the uses of these products range from areas of medical application, such as diapers for premature babies, children with enuresis, or incontinent adults, and consumer uses such as baby diapers or feminine hygiene products, the consumer needs, clinical performance and skin care requirements and technologies used in these products are similar across product categories. Because of these similarities, this chapter will cover a broad range of absorbent products used for personal health care and hygiene. It will explore the key needs of patients and consumers relating to absorbent products, hygiene implications of use, and textile properties and clinical testing methods employed during product development. We will illustrate the application of technologies using the example of a series of products designed for use in babies, from products for premature infants through toddler toilet training. Finally, we will discuss some emerging trends in this field, and provide sources that may be of use to the reader interested in obtaining additional information.

14.2 Different types of absorbent products for personal health and hygiene

The most commonly used absorbent products for personal health and hygiene are baby diapers, adult incontinence products, and feminine hygiene products.

© Woodhead Publishing Limited, 2011



14.1 Diaper components.

Absorbent products in today's market are made up of a range of materials and component parts, which are adapted and optimised for the specific application in the different products. There are, however, some common elements across all products. All contain an absorbent core, which may be made up of cellulose or polymer fibres, superabsorbent polymer, or mixtures of fluff and superabsorbent polymers. Modern products, particularly more advanced products, may also make use of one or more acquisition or transport layers that help to quickly and effectively carry fluid into the absorbent core, while maintaining dryness against the skin. These acquisition layers are typically formed from synthetic staple fibres thermally bonded in a nonwoven structure, or a structure made up of chemically or mechanically modified cellulose fibres. The absorbent structures are embedded between a layer near the skin usually called a topsheet, which is made of polymer or natural fibres, and a backsheet of polyethylene film or a film/nonwoven composite ('textile backsheet'). The backsheet can be made of a microporous material to allow for vapour permeability or 'breathability'. Most importantly, the breathable backsheet reduces the relative humidity on the surface of skin in the diaper by allowing water vapour to pass outward. Typical components of disposable hygiene products are illustrated in Fig. 14.1.

14.2.1 Baby diapers

The first modern disposable baby diapers were introduced in the 1940s and mass production began in the 1960s. While these first disposable diapers were used primarily when away from home, demand for disposable diapers expanded rapidly during the 1960s and 1980s as they became more affordable for everyday use. Since the 1990s, a steady stream of technical innovations has improved the affordability, function, and comfort of diaper products, so that disposable diapers are now used much more commonly than reusable cloth diapers in most developed countries, including Western Europe and are becoming more popular in emerging nations. It is now understood that modern disposable diapers provide skin health

© Woodhead Publishing Limited, 2011

benefits (EDANA, 2008) compared to reusable cloth diapers, without an increase in overall environmental impact (EDANA, 2007). Absorbent diaper products for babies now include baby diapers for younger infants, and diaper pants for toddlers, with taped diapers representing over 95% of the market in Western Europe (EDANA, 2004; EDANA, 2007; EDANA, 2008).

14.2.2 Adult incontinence products

Adults may lose the ability to control urine (bladder incontinence) or faeces (faecal incontinence) as a result of ageing, injury, disease, or other factors that damage the nervous or muscular control needed to maintain continence. Common factors contributing to incontinence are pregnancy and childbirth, which can affect the strength of pelvic floor structures, and prostate surgery, which can damage nerves essential to control of urination. Adults who have become incontinent must struggle with both the physical aspects of dealing with the excreta and the social and emotional aspects relating to loss of dignity and fear that their condition may be betrayed to those around them by odour, leakage, or visibility of the incontinence product. In patients who are otherwise healthy and active, a discrete product allows the continuance of normal activities without fear of embarrassment. In patients with limited mobility or who are bedridden, use of an absorbent product that protects the skin from excreta is particularly important, as these patients are at high risk of skin breakdown and bed sores (EDANA, 2009, Quality of life brochure).

Adult incontinence products take a number of forms, and the best product for a particular user will depend upon a number of factors, including sex, type and degree of incontinence, and lifestyle. All wearable disposable products are now made with fluff and superabsorbent polymers, so that even small, thin products can contain large volumes of liquid and lock the liquid inside so that skin remains dry. Products include body worn all-in-one products (a taped product for severe faecal or urinary incontinence) and pads (worn as an insert in a special pant or in normal underwear, for light, medium, or severe incontinence), and male pouches (worn with an incontinence pant or tight underwear, for mild urinary incontinence).

14.2.3 Feminine hygiene products

In recent decades, disposable absorbent feminine hygiene products have largely replaced older methods of managing menses for women in the developed nations. Products include internal tampons, full-sized sanitary napkins or towels, both for use during menstruation, and panty shields, which may be used to protect undergarments from light menstrual flow or spotting or from vaginal discharge and to maintain cleanliness. In terms of their physical design and basic components, the most advanced sanitary napkins and panty shields make use of many of the

© Woodhead Publishing Limited, 2011

same technologies developed for use in baby diapers, including superabsorbent polymers and nonwoven top sheets that keep skin feeling dryer. The requirements for all these products are that they absorb and retain fluid, stay in place, prevent odour, and be comfortable to wear. In Western Europe, sanitary towels make up approximately 45% of feminine hygiene products sold, while panty shields make up about 37% and tampons about 18% (EDANA, 2004 data).

14.3 Key issues of absorbent hygiene products

14.3.1 Consumer needs

Specific consumer needs vary by user and type of product, but there are some consumer requirements for absorbent hygiene products that are common across categories. Users of baby diapers, adult incontinence products, and feminine hygiene products all require a product that facilitates cleanliness by absorbing and retaining fluid, protects the skin from damage due to exposure to excess moisture and digestive enzymes, does not leak, and is comfortable, convenient and discrete. Consumers also desire to use products that have minimal adverse effects on the environment. Advances in technology have led to the development of products that come very close to the ideal in many aspects, and work continues to better understand and address the needs of consumers who use disposable absorbent hygiene products.

Baby diapers

Consumer needs with regard to baby diapers are particularly diverse, as it is important to consider the needs of both the baby and the caregiver, and those needs may differ. For example, for a baby, the sensoric properties inside the diaper, like the dryness and the softness of the topsheet, play an important role in comfort during wear, while the mother may pay more attention to the absorbency and leak protection of the diaper. The diaper has to adapt to changing requirements over the course of a day (for instance, with activity during playtime versus less active phases during sleep), and to different needs as the baby grows and develops. Over time, the baby grows in size, capability, and activity level, and experiences changes in diet (from liquid to more solid food); each of these developments is associated with changes in the performance properties required of the diaper. Common needs across all stages of development include the need for superior urine absorbency, leak protection, dryness, and rash protection. Since their introduction in the 1940s, disposable diapers have evolved through a steady stream of product innovations, so that the best disposable diapers now offer very good containment of urine and faeces, along with excellent skin protection (Odio and Friedlander, 2000; Adam, 2008). Further efforts to improve these products include changes that improve the feel of the product during wear, make changing

© Woodhead Publishing Limited, 2011

easier, and adapt to the changing ability of the child to cooperate with changes and foster independence.

Adult incontinence

Adult incontinence occurs in both men and women and can range from light leakage of urine to complete loss of control of urine and faeces. The majority of adults with incontinence are women, and most of these experience light urinary incontinence. Consumer research has shown that many women use panty liners or sanitary napkins designed for menstruation to control small amounts of leakage because they are comfortable and discrete. Women with heavier leakage may use full-size sanitary napkins or pads specifically designed for female incontinence to achieve greater absorbency. Key consumer needs in this category include the need for protection/absorption (i.e., dryness, odour control, no leakage, no bunching), comfort/discretion (not bulky, acceptable feel while wearing, not noisy), a sense of being secure and in control (no social restrictions), and a need to forget about bladder weakness. Key incontinence product requirements are the ability to quickly acquire and store urine (which is more fluid, has lower viscosity, and is expelled under more pressure than menstrual fluid) and to deliver wearing comfort, as average wear time is between six and ten hours.

Feminine hygiene

Disposable absorbent products for feminine hygiene during menstruation are an important part of life for millions of women. The average woman will have approximately 13 cycles each year for about 37 years and will spend more than six years of that period menstruating. Menstrual flow varies with age, number of children, and use of hormones or intrauterine devices, and typically is heaviest during the second and third days of each period. Products include tampons, panty liners, and pads. Research has identified a number of consumer needs in this category, including the need to feel clean and dry, to be protected and in control, and for comfort and convenience. Key product performance requirements include the ability to handle a range of menstrual flows under a variety of use conditions and activities, to be friendly to skin and comfortable, and to be easy to use and to dispose of. The most advanced pads for menstrual protection make use of unique topsheets that funnel fluid into the absorbent core, maintaining a clean, dry feeling. The core of superabsorbent polymers rapidly absorbs moisture and locks it away, minimising leaks and controlling odour. Odour control can be done via different routes including slowing down odour generation by absorbing liquid and transferring it into a gel, using odour absorbent materials such as zeolithes, cyclodextrines or the like or inhibiting bacteria growth with chemical or natural ingredients such as green tea extract. A backsheet prevents moisture in the core from exiting the pad and staining clothing. Backsheets may be completely

© Woodhead Publishing Limited, 2011

impermeable or, as it is the case in most modern backsheets, semi-permeable ('breathable'), allowing water vapour but not liquid water to pass. This property contributes to comfort (Schaefer *et al*., 2002). Research continues to improve both the functional performance of feminine hygiene products and the consumer experience during use.

14.3.2 Skin protection properties of absorbent hygiene products

Skin protection is a particularly important issue in the context of absorbent hygiene products, as the presence of urine, faeces, or menses on skin creates conditions that facilitate the development of irritant dermatitis. This process has been most extensively studied by investigating diaper dermatitis, but many of the basic principles are applicable to the use of other absorbent hygiene products (Runeman, 2008).

Many factors play a role in the development of diaper dermatitis, including humidity, changes in pH, mechanical friction, chemical challenges, and the skin microorganisms. Berg (1988) proposed a model for the development of diaper dermatitis. In this model, healthy skin of the diaper area becomes compromised following exposure to moisture, mechanical forces, and increased pH (resulting from creation of ammonia from urine via action of ureases from faecal microbes). Wet skin is more prone to frictional damage as a result of its higher coefficient of friction compared with dry skin. The resulting damaged skin has impaired barrier function and is more susceptible to penetration by irritants and colonisation by microorganisms such as *Candida albicans* and *Staphylococcus aureus*. This model makes clear the importance of controlling skin wetness and pH in order to maintain skin health in the diaper area.

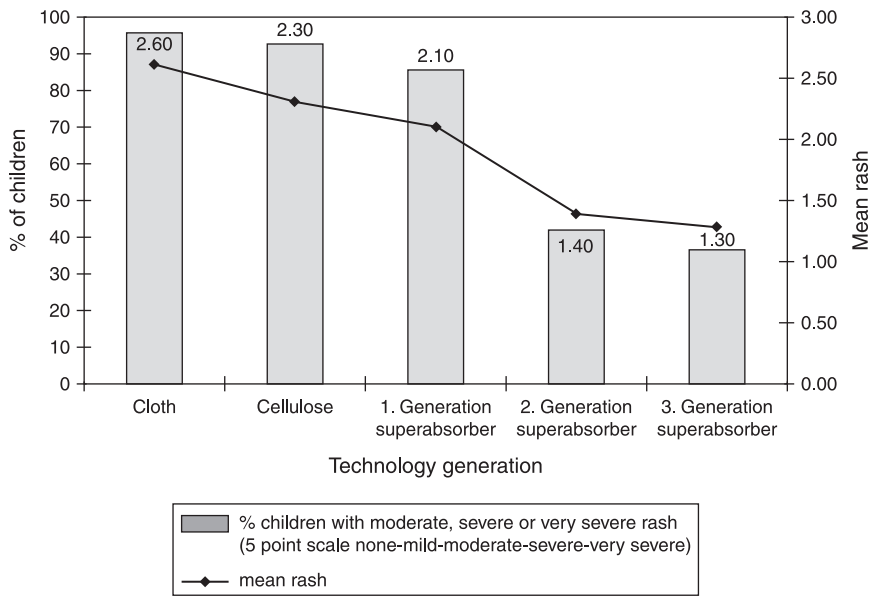
Baby diapers have evolved over time to better meet the needs of caregivers and babies for better absorption and containment of excreta. In the early twentieth century, consumers in most Western countries used cotton fabric diapers that were pinned in place and covered by waterproof pants (Adam, 2008). By mid-century, disposable diapers with a rectangular shape, backsheet film, and fluff pulp core were introduced. These diapers were later improved by the use of more absorbent materials, leg cuffs to improve fit and prevent leakage, and better fasteners. Advances in baby diaper technology have contributed greatly to the promotion of healthy skin in the diaper area. The introduction of superabsorbent polymers for use in diaper cores increased the speed of liquid acquisition and overall absorbency, moving urine away from the skin and locking it away, keeping the skin dryer.

This benefit is particularly important in infants, as they are particularly prone to diaper rash due to the regular exposure of skin with excreta and the resulting effects from digestive enzyme (re)activation and increased coefficient of friction of wet skin (Adam, 2008). The benefit of superabsorbent diapers in protecting

© Woodhead Publishing Limited, 2011

babies' skin is illustrated by data showing that the frequency of moderate to severe diaper dermatitis declined by 50% in the period following introduction of diapers using cross-linked sodium polyacrylate polymers ('superabsorber') (Odio and Friedlander, 2000). Further decline of diaper dermatitis was seen with the improvement of superabsorbers from the first to the third technology generation, as shown in Fig. 14.2.

Another innovation that promoted skin health was the development of lotion-impregnated inner topsheets that transfer a petrolatum-based ointment to the skin. A normal stratum corneum prevents the penetration of toxic substances and microorganisms. Damaged stratum corneum allows an increased loss of water (transepidermal water loss; TEWL) and penetration of irritants. Secondarily, microorganisms such as *Candida albicans* can colonise those compromised skin areas and contribute to further damage leading to severe rash episodes. Application of barrier preparations (such as the petrolatum-based ointment used in some diaper topsheets) can protect normal skin when the stratum corneum is at risk of damage or can be used in an attempt to improve barrier function in an already compromised stratum corneum and provide protection from wetness (Atherton, 2004). This ointment layer supports skin barrier and protects the skin from excessive hydration and irritants by providing a hydrophobic barrier without occlusion. Studies have shown that ointment-containing diapers provide improved skin protection (Odio *et al*., 2000a,b; Tate *et al*., 2007). The presence of the



14.2 Development of diaper rash with different diaper technologies.

© Woodhead Publishing Limited, 2011

ointment on the skin also makes cleaning easier, so fewer irritating contaminants are left on the skin. In a double-blind, randomised trial in children deemed by their parents to be especially susceptible to diaper dermatitis, use of a petrolatum-containing diaper was associated with statistically significant, sustained reduction in the severity of dermatitis compared with a control product (Odio and Friedlander, 2000).

A further development that improves skin health is the use of vapour-permeable ('breathable') membranes rather than impenetrable films for the outer diaper cover. These covers allow movement of water vapour and air, while retaining liquid urine within the diaper. Diapers with these microporous covers have been shown to reduce both the elevated relative humidity and skin hydration found under more occlusive diapers (Grove *et al*., 1998). Use of breathable diapers reduced the incidence of infection with *Candida albicans* and the prevalence of diaper dermatitis compared with non-breathable diapers (Akin *et al*., 2001). This technology has also been applied to feminine hygiene products; breathable back sheets in panty liners have been shown to reduce temperature, humidity, pH and the number of microorganisms on the vulvar skin compared with non-breathable liners (Schaefer *et al*., 2002; Runeman *et al*., 2003; Runeman *et al*., 2004).

Adults who use absorbent incontinence products may experience dermatitis as a result of the same basic factors seen in infants who use diapers, but there are some factors that are different. Specifically, the skin of elderly persons is more fragile and subject to injury, with poorer healing than baby skin. Also, urinary incontinence in adults is not always accompanied by faecal incontinence, so effects resulting from the mixing of urine and faeces are not a problem for many adult users. Skin health of elderly under nursing care may be compromised by both incontinence and by pressure sores or moisture lesions, so that it is sometimes difficult to identify the primary cause of a lesion. The incidence of skin problems in institutionalised patients is related to the quality of care, patient mobility, the quality of the incontinence products being used, and the medical, physiological and mental condition of the patient (EDANA, 2008). In general, occlusion and wetness contribute to skin problems in adults with incontinence as they do in babies, so products that are highly absorbent and 'breathable' are likely to be most protective of skin health.

External feminine hygiene products have been tested in many parts of the world under a wide range of conditions and have been found to have no adverse skin effects (EDANA, 2008). Concern that superabsorbent pads might cause drying of the skin and resultant low humidity dermatitis has not been proven to be true. The use of sanitary napkins is limited to days around and during the menstrual period; such intermittent use might be expected to have less impact on skin than products that are used daily and continuously, like baby diapers and adult incontinence products. The use of panty liners for protection between periods is not expected to result in any skin problems, as breathable panty liners with acidic cores produce

© Woodhead Publishing Limited, 2011

skin conditions (i.e., temperature, pH, and microflora) that are very similar to those present when the product is not in use (EDANA, 2008).

14.3.3 Hygiene implications

Disposable superabsorbent hygiene products promote cleanliness by containing bodily fluids and excreta and allowing them to be disposed of in an appropriate way. Faeces contain up to 10^{10} bacteria per gram of weight (Frank *et al*., 1998; Hoogkamp-Korstanje *et al*., 1979) and the faecal microbiota in infants is estimated to consist of 20 genera and 100 species (Benno *et al*., 1984). Several epidemiological studies have shown that diapered infants can contribute significantly to environmental contamination with microorganisms, especially in daycare settings (Campbell *et al*., 1988; Van *et al*., 1991a; Van *et al*., 1991b). Diarrhoea is common in infants and children, and proper hygiene, including safe disposal of faeces, is important in prevention of the spread of diarrhoea (WHO, Huttly *et al*., 1987). In addition to providing skin protection benefits, disposable superabsorbent diaper products provide better containment of the excreta, reducing environmental spread of pathogenic organisms. This benefit may be of particular value in group settings: a panel of experts has cited reduction of faecal contamination in day care settings as one advantage of using highly absorbent and leak protective diapers (EDANA, 2008). In addition, a randomised trial in a day care setting has shown that significantly fewer objects were contaminated with faecal coliform bacteria in rooms in which children wore disposable superabsorbent diapers compared with double cloth diapers and plastic overpants when no overclothes were worn (Van *et al*., 1991b). The risk for diarrhoeal illness in day care centres has been clearly linked with contamination of hands and items such as toys (Laborde *et al*., 1993), so prevention of such contamination is an important step in controlling the spread of illness in this setting.

It should also be noted that, when thrown away in the rubbish, the soiled disposable diaper is typically wrapped tightly using the diaper tapes, providing additional containment of the faeces until safely disposed of by incineration or in a landfill. In contrast, reusable cloth diapers must be retained and laundered, allowing many opportunities for contamination of hands, surfaces, or other aspects of the environment with faecal organisms.

Hygiene issues for adult incontinence products are similar to those for baby diapers. In institutional settings, especially, the ability to confine and dispose of urine and faeces with a minimum of effort and without contamination of the environment is paramount. Use of modern disposable absorbent incontinence products should reduce the amount of time required to clean and care for incontinent elderly or frail patients, the costs and time needed to wash soiled clothing and bedding, and the risk of spreading illness in the institution through contamination. In active adults, use of modern, highly absorbent incontinence

© Woodhead Publishing Limited, 2011

products allows continuation of a normal routine outside the home, without fear of leakage and embarrassment in public.

Studies on the survival and movement of enteric viruses and bacteria in landfills have demonstrated that the microbial population of the leachate decreases with time (Pahren, 1987). Indicator organisms of faecal contamination and enteric viruses are extensively inactivated by the leachate in landfills and viruses do not escape from landfills (Sobsey, 1978; Sobsey *et al*., 1975). Disposal of baby diapers, adult incontinence products, or feminine hygiene products in proper solid waste landfills has not been associated with any risk of disease to waste collection workers or the public. In contrast, recent research in China has been shown that the use of disposable diapers provides a significant advantage over cloth diapers in the microbial contamination of skin and household surfaces (Adam and Odio, 2009).

14.4 Testing of absorbent hygiene products

14.4.1 Testing of technical properties

As disposable hygiene products have become more complex and their materials more sophisticated, researchers have developed a number of testing methods for use during the product development process. These methods ensure that new products will deliver both the functional performance and the wear experience expected by the consumer. This testing includes measurement of chemical, physical, and absorbent properties of raw materials and test products. Some tests, such as those measuring raw material properties or speed of fluid acquisition, are relatively simple, while others, such as determination of fit during use, may be more complex. A particular challenge in this category is the development of laboratory testing methods that simulate the variety and complexity of actual product use and allow correlation of different physical parameters (flow levels, loading, activities, product shape and fit with anatomy during different activities, etc.). The most important product improvements in disposable hygiene products (e.g. superabsorbent materials, fluid-acquisition topsheets) have come about through in-depth understanding of the physical properties of materials and their interactions with fluids under use conditions, often obtained from returned products after usage by consumers. Detailed and exhaustive laboratory testing makes possible the development of optimal prototype products for progression to human clinical testing.

Laboratory methods for testing of absorbent hygiene products include testing of properties related to skin dryness (rewet or mannequin methods), breathability (water vapour transmission test), leakage (absorption time, run-off, and mannequin methods) and product fit (moving mannequin methods and measurements of stretch). A variety of absorption tests have been developed in order to examine different parameters related to fluid handling by the absorbent system (retention,

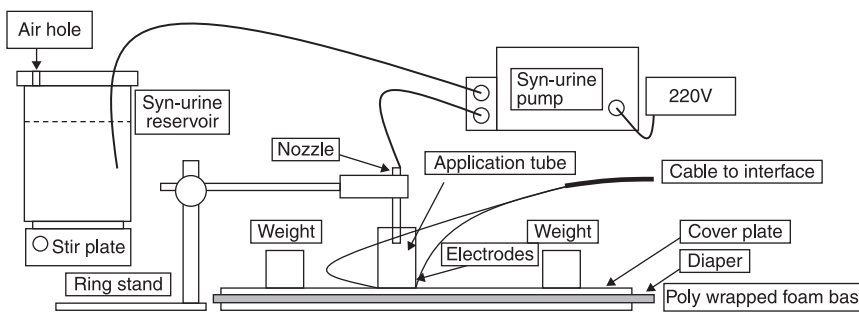
© Woodhead Publishing Limited, 2011

rewet, released fluid percentage) (Hardy, 2009). Tests of the total absorption capacity (centrifuge retention test, Rothwell test) are applied today for quality assurance testing, but not for comparisons of different products, as modern products can vary a lot in capacity without showing a difference in performance. For light incontinence pads for women, it has even been recommended that the Rothwell test be withdrawn completely (Cottenden *et al*., 2006). If a lotion is applied to the topsheet of an absorbent hygiene product, methods to measure lotion transfer are also employed, as are measures of the amount of free fluid on skin. Speed of fluid acquisition is also critical in adult incontinence products, as are issues of leakage and fit under conditions simulating actual use. The ability of materials to neutralise odours associated with urine is also important in this category.

In many cases, laboratory testing of materials may employ substitutes for bodily fluids such as simulated urine (e.g. 0.9% saline solution) or simulated menstrual fluid. These materials are designed to behave like the natural materials but avoid the problems of obtaining and handling biomaterials.

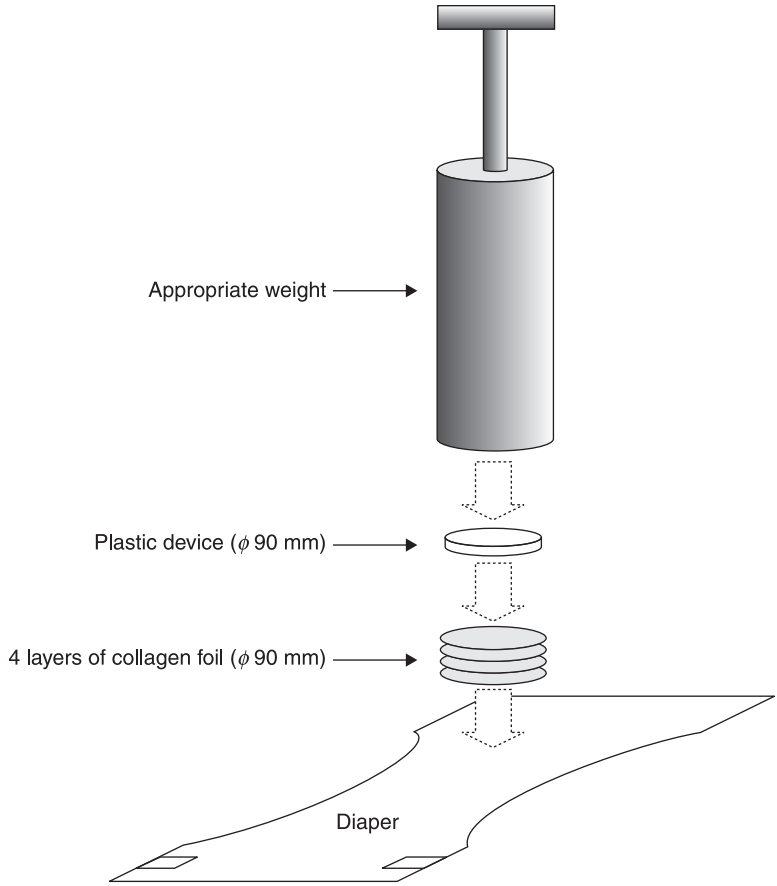
As examples, we describe here the principles of two of the most common methods used to characterise absorbent hygiene products, 'absorption time' and 'rewet'.

Absorption time (Fig. 14.3), i.e. the time needed to absorb a certain amount of fluid, is strongly correlated to the probability of leakage. Figure 14.4 shows a drawing of a typical apparatus used for this measurement: The test product, here a diaper, is laid with the backsheet side onto a polyurethane-foam base and covered with a cover plate, as shown. Weights are placed onto the cover plate to simulate the weight of the baby lying on the diaper. Because of the foam base the pressure is distributed equally across the diaper. The cover plate has a hole which is placed over the area, where the diaper typically absorbs urine. An application tube containing an electrode connected to a computer is mounted over that hole. A certain amount of synthetic urine is pumped into the application tube and with help of the electrode the time is measured until all liquid of the tube is absorbed



14.3 Schematic drawing of a device to measure 'absorption time' of a diaper.

© Woodhead Publishing Limited, 2011



14.4 Schematic drawing of a 'rewet' measurement.

by the diaper. This is repeated three to four times to simulate the repeated urinations of a baby. Results are recorded as absorption rates, i.e. volume per time (ml/s).

Rewet (Fig. 14.4) methods are used to assess the amount of liquid that has been absorbed but is squeezed out again under pressure, e.g. when the wearer sits down. A low rewet is important to keep the wearer's skin dry. Figure 14.4 shows a schematic setup of a rewet method: A diaper is loaded with a certain amount of liquid. After a waiting time (typically 5–10 minutes) an absorbent material is laid on the topsheet in the area, where urine is usually absorbed in real use. The material is weighted before. Often filter paper is used as absorbent material, but modern methods use collagen instead, which has absorbent properties closer to human skin. Then a weight is applied onto the material, simulating the wearer's weight when sitting down. After the weight is removed, the amount of liquid absorbed by the absorbent material is determined by weighing the material again and calculating the difference. Results are reported in weight, either as grams or milligrams.

© Woodhead Publishing Limited, 2011

14.4.2 Consumer testing of absorbent hygiene products

Consumer testing is an important methodology in the area of absorbent products, given they are usually used by consumers rather than professionals. As discussed earlier, consumers expect not only a good technical performance, such as good leakage protection, but also properties like good wearing comfort and fit, which can not be tested sufficiently in the laboratory, due to the many different elements that play a role in these benefits. Therefore, only in-use testing can adequately compare different products or provide guidance for product improvements. Different consumer testing techniques are used depending on the aims of the research:

- *Small base testing* in 10 to 30 product users is used to determine a specific product property such as the right dimension to deliver a good fit. In these cases, different product types are compared using the same set of panellists. In a typical study, the panellists will put on the product and measurements will be taken directly after application and after a certain wear time. After wear, the product fit will be checked for signs of slippage and skin will be examined for any evidence of pressure marks.
- *1-on-1 interviews or focus group discussions* after product usage are used to assess how the product was perceived by the wearers or, in case of baby diapers, by the care givers. The number of consumers interviewed can vary, but is typically at least 20 to 30 people.
- *Diary studies* are used for example to assess experience under realistic in-use conditions. They will typically be conducted in 100 or more users, who complete diary entries after each product usage. Studies usually run for one to two weeks or, in the case of feminine hygiene products, throughout one menstruation period. The diaries are adapted to the research subject; examples of typical questions in a diary would be if a product had leaked, where it had leaked, and how long it was used. Panellists may also be asked to return used products for a laboratory assessment, so that the technical measurements on the used products can be compared with it's in-use performance as recorded in the diary.
- *Consumer perception tests* might be used to determine the perception of a product by consumers. They are typically placed in 100 or more consumers, who are provided with enough products to use for one to two weeks. Consumers are asked to fill in a questionnaire after the product usage, in which they are asked about their perception of the product (e.g. 'How do you rate the product quality overall?'). In perception tests, different products might be placed with the same consumer group (paired comparison test) or different sets of consumers (parallel test), depending on the research objective.

14.4.3 Clinical properties and testing

Although well-designed laboratory test methods are critically valuable to the development process, the ultimate testing of any new absorbent hygiene product

© Woodhead Publishing Limited, 2011

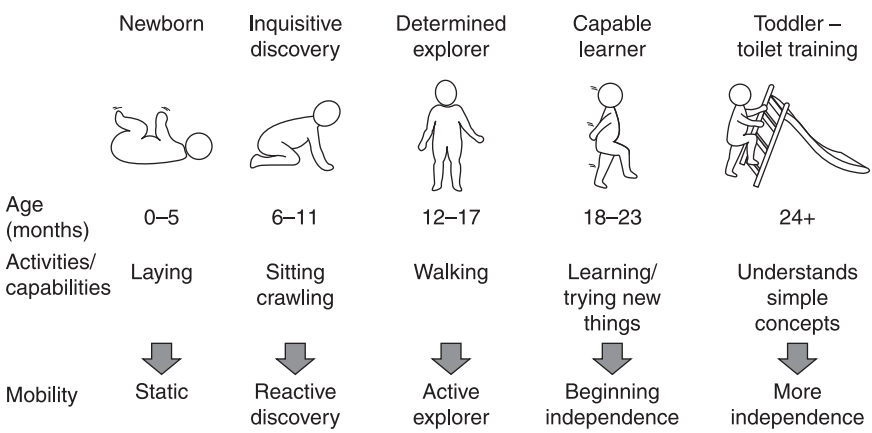
takes place in clinical tests of actual use by typical consumers. Understanding the way consumers use and experience the product and how it functions under these conditions is critical to optimisation of the product design.

Historically, diaper in-use studies were performed under standardised in-use conditions using expert skin grading as the primary endpoint. Subsequently, with emerging biophysical test methods, physiological endpoints such as capacitance to assess skin hydration, measurement of skin pH using specific flat glass electrodes, and measurement of water evaporation through or from the stratum corneum (TEWL or SSWL: skin surface water loss) were used. Evaporation was not only used to measure the status of the stratum corneum barrier but also to determine the ability of a diaper absorbent core to keep the skin dry, absorb fluid, and keep urine residue from skin.

Recently, additional methods to investigate the water dynamics in infant stratum corneum have been described, using in vivo Raman Spectroscopy for profiling of water and natural moisturisation factors in infant stratum corneum (Nikolovski *et al.*, 2008).

14.5 Application example: diapers – adapting products from premature babies to toilet training

While baby diapers are used for a relatively short period during the human life span, this period of use includes a wide range of developmental progress, from tiny premature babies to toddlers undergoing toilet training. Therefore, diapers for different stages of baby development are excellent examples to showcase the application of the different technologies used in absorbent hygiene products. Figure 14.5 illustrates five distinct stages of development that can be defined



14.5 Stages of development in a baby.

© Woodhead Publishing Limited, 2011

during the diapering period, each with a different level of physical and mental capabilities.

To further illustrate the effects of these stages on product requirements, the differences between products made for three of these stages are described below:

- *Newborn stage*: In the first three to five months after birth, the parents are especially concerned with protecting their newborn baby's skin and making the transition from the mother's womb into the world as smooth and comfortable as possible. Babies in this phase experience the world especially through feeling and listening, while the visual sense is not yet well developed. Thus, in the diaper context the tactile properties are particularly important. As babies in this phase usually have liquid or soft stool, protection against bowel movement leaks is a particular performance need. Therefore, diapers for newborns are usually made from especially soft materials, and they often feature specific technologies to allow absorbency of soft stool and good leakage protection. As for any stage, absorbency of urine to provide skin dryness and urine leakage protection is important, too.
- In the '*determined explorer' stage*, babies have become able to walk and are very mobile, so it is important that this mobility not be inhibited by the diapers. Therefore, diapers for babies in this stage feature not only good absorbency but also elastic elements such as stretch sides to adapt to the baby's body during movement, and are made especially thin and narrow between the legs for a good and comfortable fit.
- Once babies enter the '*capable learner' stage*, they start to become more independent from the parents and more self conscious. Therefore, they try to do many tasks on their own that parents have previously done for them, such as trying to dress themselves or taking off/putting on diapers by themselves. Putting on a classical taped diaper without help is very hard even for a grown-up; therefore, diapers that are shaped like a pant and can be pulled up are the right choice for babies in this stage.

As these examples show, different technologies need to be applied to develop products meeting the different needs of users under various circumstances.

14.6 Future trends

For all absorbent hygiene products the trend for improvements in skin protection and wearing comfort via better softness, improved breathability and thinner and more flexible products can be expected to continue. In addition, there is an increasing trend to improve the sustainability of products, especially by making products more environmentally compatible and by decreasing the overall impact on the environment throughout the whole life cycle of products.

© Woodhead Publishing Limited, 2011

14.6.1 Technology trends

One key trend is the continuous improvement of the absorbing materials used for absorbent hygiene products, in particular the superabsorbent polymers. Improvements in the chemistry of these absorbers make it possible to have much higher concentrations of them inside the absorbent cores, so the amount of cellulose fibres can be reduced, leading to very thin and flexible yet highly absorbent products.

Another trend is the introduction of new film and nonwoven materials, made possible by new fibre chemistries that provide more softness and breathability at affordable costs, improving the wearing comfort of incontinence products and feminine pads.

In the area of skin care, some manufacturers have started to add cosmetic formulations to the topsheets to provide better skin care. It is likely that this will continue with improved formulations and ingredients.

Finally, technology is being used to improve the environmental profile of the products. New materials provide the same performance with lower weight, creating positive effects throughout the product life cycle by minimising energy use for production and transport and reducing waste. Replacing oil-based materials with materials based on renewable resources is an important trend. While some manufacturers have started to use biodegradable materials, this approach is not without problems, as composting diapers and incontinence products causes concerns because of the high load of faecal microorganisms. These issues will need to be resolved before the full potential of biodegradable materials can be realised.

14.6.2 Sustainability

In a world in which environmental and social responsibility have become serious concerns, all manufacturers need to understand the environmental impact of their products. Life cycle assessments (LCAs), which evaluate the environmental impact of the product from the production of raw materials through to final disposal, have been performed for all categories of absorbent hygiene products. Across all categories, product improvements in recent decades did not only lead to better performance and improved skin health, but also have resulted in reduced weight of both products and packaging, resulting in substantially reduced environmental impact compared to typical disposable products of the 1980s (EDANA sustainability report, 2007). Using the LCA method to generate a holistic picture of the environmental performance of absorbent hygiene products over time (EDANA, 2007) established that there have been significant improvements. For diapers for example:

- The average diaper weight has been significantly reduced by almost 40% in a period of 17 years, from around 65 g in 1987 to 56 g in 1995 and to 41 g in 2005.

© Woodhead Publishing Limited, 2011

- The weight of packaging has been reduced by 41% from 8.0 kg per 1000 pieces in 1987 to 4.7 kg per 1000 pieces in 2005.
- There has been an overall reduction in the environmental impacts of using diapers over the diapering period of one child of 32% between 1987 and 2005.
- The global warming and the summer smog impacts of diapers reduced between 1987 and 2005 by 37% and 43%, respectively.

Similar positive trends have been shown with incontinence products and their packaging. The LCA study has been conducted by the German research institute IFEU (Institut für Energie- und Umweltforschung, Heidelberg) and has been independently peer-reviewed according to the ISO 14040 series standards.

Many consumers are concerned about the relative environmental impacts of reusable cloth diapers and disposable diapers. The impacts of cloth and disposable diapers have been evaluated in numerous LCA studies around the world, with the overall conclusion that neither diaper option is environmentally preferable. In 2005 and 2008, the United Kingdom's Environment Agency assessed three diaper types: disposable, home laundered cloth diapers, and commercially laundered cloth diapers delivered to the home. This LCA study evaluated the potential environmental impacts associated with an average child wearing nappies during the first 2.5 years of life. The environmental impacts indicators assessed included: resource depletion; climate change; ozone depletion; human toxicity; acidification; fresh-water aquatic toxicity; terrestrial toxicity; smog; and eutrophication. The conclusion was that there is no significant difference between the environmental impacts of the three diapering systems; none of the systems studied is more or less environmentally preferable. The environmental impacts of the diapering systems are different, however. Environmental impacts are linked to the energy, water, and detergents needed to clean cloth diapers, and to raw material production for disposable diapers. Consistent with previous industry association LCA studies (EDANA, 2007), the UK study indicated that the potential environmental impacts of disposable diapers could be reduced by decreasing product weight and improvements in materials manufacturing, while the impact of reusable cloth diapers could be minimised by reducing the energy required for washing and drying. In its update in 2008 the LCA study also confirmed improvements for disposable diapers, e.g. 12% less Global Warming Potential and 13.5% less material usage since its first study in 2005 due to manufacturing changes. In terms of Global Warming Potential, the UK Environment Agency showed 550 kg of carbon dioxide equivalents for disposable diapers, while this number was higher for cloth diapers with 570 kg of carbon dioxide equivalents.

Although raw material production is the primary driver of potential environmental impacts for disposable diapers, there is public interest related to used diaper waste. The UK study also found that the impact of waste from the three diapering systems did not contribute substantially to overall municipal solid waste in the UK. The global warming and non-renewable resource depletion

© Woodhead Publishing Limited, 2011

impacts for the 2.5 years in which a child wears diapers are similar to the impact of driving a car for between 2100 and 3500 km (EDANA, 2007).

Waste from absorbent hygiene products accounts for less than 0.5% of total solid waste in the European Union (EDANA, 2007). Used hygiene products are most commonly disposed in sanitary landfills or incinerated with the heat from burning used to generate steam or electricity. In a few areas used products undergo a controlled form of composting, through mechanical-biological pretreatment or anaerobic digestion prior to recover energy or organic materials, and reduce the residue that is incinerated or landfilled. Manufacturers continue to work to identify ways to reduce the environmental burden associated with products throughout their life cycles. This goal may be accomplished by making more efficient use of natural resources and reducing waste, energy use, and carbon dioxide emissions.

14.7 Sources of further information and advice

Helpful, up-to-date information in this area can be found on the webpages of EDANA, the International Association Serving the Nonwovens and Related Industries based in the EU (www.edana.org), the Absorbent Hygiene Products Manufacturers Committee (HAPCO) of EDANA (www.hapco.edana.org), INDA, the Association of Nonwoven Fabrics Industry based in the US (www.inda.org), and similar, smaller associations in several countries.

14.8 Acknowledgements

The authors acknowledge the assistance of Lisa Bosch in the preparation of this chapter, Dr Mattias Schmidt for reviewing, and Annie Weisbrod PhD and Dr Ioannis Hatzopoulos for environmental sustainability and LCA perspective.

14.9 References

Adam R (2008). Skin care of the diaper area, *Pediatr Dermatol*, 25, 427–433.

Adam R and Odio M (2009). Beneficial effects of diapers and wipes for the care of sensitive infant skin. Poster at the 11th World Congress of Pediatric Dermatology, Bangkok, Thailand.

Akin F, Spraker M, Aly R, Leyden J, Raynor W and Landin W (2001). Effects of breathable disposable diapers: Reduced prevalence of *Candida* and common diaper dermatitis, *Pediatr Dermatol*, 18, 282–290.

Atherton DJ (2004). A review of the pathophysiology, prevention and treatment of irritant diaper dermatitis, *Curr Med Res Opin*, 20, 645–649.

Benno Y, Sawada K and Misuoka T (1984). The intestinal microflora of infants: composition of fecal flora in breast-fed and bottle-fed infants, *Microbiol Immunol*, 28, 975–986.

Berg RW (1988). Etiology and pathophysiology of diaper dermatitis, *Adv Dermtol*, 3, 75–98.

Campbell RL, Bartlett AV, Sarbaugh FC, Pickering LK (1988). Effects of diaper types on diaper dermatitis associated with diarrhea and antibiotic use in children in day-care centers, *Pediatr Dermatol* 5(2), 83–87.

© Woodhead Publishing Limited, 2011

Cottenden *et al*. (2006). A critical investigation of ISO 11948-2 and ISO 11948-1 for predicting the leakage performance of small disposable incontinence pads for lightly incontinent women, *Med Eng Phys*, 28, 42–48.

EDANA (2004). WE market shares, 2004. Available at: www.edana.org.

EDANA (2007). Sustainability Report 2007–2008: Absorbent hygiene products, EDANA, Brussels.

EDANA (2008). Summary report of sustainability panel discussion: The skin health and hygiene benefits of absorbent hygiene products and wipes, EDANA, Brussels.

EDANA (2009). Quality of Life and absorbent Hygiene Products. The social dimension of sustainability. EDANA

Frank AH, Harmsen HH, Raangs GC, Jansen GJ, Schut F and Welling WH (1998). Variations of bacterial populations in human feces measured by fluorescent in situ hybridization with group-spectific 16S rRNA-targeted oligonucleotide probes, *Appl Environ Microbiol*, 64, 3346–3354.

Grove GL, Lemmen JT, Garafalo M and Akin FJ (1998). Assessment of skin hydration caused by diapers and incontinence articles, *Curr Probl Dermatol*, 26, 183–195.

Hardy P (2009). Baby diaper absorbent cores: new tests for effective core design. Nonvovens Industry. Available: www. Nonwovens_industry.com.

Hoogkamp-Korstanje JA, Lindner JG, Marcelis JH, den Daas-Slagt H, de Vos NM (1979). Composition and ecology of the human intestinal flora, *Antoine van Leeuwenhoek* 45(1), 35–40.

Huttly SR, Blum D, Kirkwood BR, Emeh RN, Feachem RG (1987). The epidemiology of acute diarrhoea in a rural community in Imo state, Nigeria, *Trans R Soc Trop Med Hyg*, 81(5), 865–870.

Laborde DJ, Weigle KA, Weber DJ and Kotch JB (1993). Effect of fecal contamination on diarrheal illness rates in day-care centers, *Am J Epidemiol*, 138, 243–255.

Nikolovski J, Stamatas GN, Kollias N and Wiegand BC (2008). Barrier function and water-holding and transport properties of infant stratum corneum are different from adult and continue to develop through the first year of life, *J Invest Dermatol*, online publication, doi:10.1038/sj.jid5701239.

Odio M and Friedlander SF (2000). Diaper dermatitis and advances in diaper technology, *Curr Opin Pediatr*, 12, 342–346.

Odio MR, O'Connor RJ, Sarbaugh F and Baldwin S (2000a). Continuous topical administration of a petrolatum formulation by a novel disposable diaper. 1. Effect on skin surface microtopography, *Dermatology*, 200, 232–237.

Odio MR, O'Connor RJ, Sarbaugh F and Baldwin S (2000b). Continuous topical administration of a petrolatum formulation by a novel disposable diaper. 2. Effect on skin condition, *Dermatology*, 200, 238–243.

Pahren HR (1987). Microorganisms in municipal solid waste and public health implications, *CRC Crit Rev Environ Control*, 17, 187–228.

Runeman B (2008). Skin interaction with absorbent hygiene products, *Clin Dermatol*, 26, 45–51.

Runeman B, Rybo G, Larkö O *et al*. (2003). The vulva skin microclimate: influence of panty liners on temperature, humidity, and pH, *Acta Derm Venerol*, 83, 88–92.

Runeman B, Rybo G, Forsgren-Brusk U, *et al*. (2004). The vulvar skin microenvironment: influence of different panty liners on temperature, pH and microflora, *Acta Derm Venerol*, 84, 277–284.

© Woodhead Publishing Limited, 2011

Schaefer P, Bewick-Sonntag C, Capri MG and Berardesca E (2002). Physiological changes in skin barrier function in relation to occlusion level, exposure time and climatic conditions, *Skin Pharmacol Appl Skin Physiol*, 15, 7–19.

Sobsey MD (1978). Field survey of enteric viruses in solid waste landfill leachates, *Am J Public Health*, 68, 858–864.

Sobsey MD *et al*. (1975). Studies on the survival and fate of enteroviruses in an experimental model of a municipal solid waste landfill and leachate, *App Microbiol*, 30, 565–574.

Tate M, Grove G, Joch R, Laabs J *et al*. (2007). Dye esclusion as a means to measure wetness protection of human skin, *Skin Res Technol*, 13, 293–298.

Van R, Morrow AL, Reves RR and Pickering LK (1991a). Environmental contamination in child day-care center, *Am J Epidemiol*, 133, 460–470.

Van R, Wun C-C, Morrow AL and Pickering LK (1991b). The effect of diaper type and overclothing on fecal contamination in day-care centers, *JAMA*, 265, 1840–1844.

© Woodhead Publishing Limited, 2011

15

Bio-functional textiles

S. LIU, University of Manitoba, Canada and G. SUN, University of California, Davis, USA

Abstract: Different types of bio-functional textiles with bio-sensing, antibacterial and bio-catalytic functionalities are reviewed in this chapter. Evaluation of the bio-functional effects and safety is outlined. Several successfully commercialized bio-functional textiles such as mosquito repellent garments, antibacterial wound care dressing and cosmetic textiles are also introduced. Finally, both physical and chemical manufacturing techniques of bio-functional textiles are described.

Key words: antibacterial activity, insect repellent function, bio-catalytic property, bio-sensing textiles, cosmetic textiles.

15.1 Introduction

Historically, the term 'bio-functional textiles' generally refers to antimicrobial textiles. With the emerging needs and new technological advancement, this scientific field has been expanding. Various new bio-active functions have been imparted to textile materials, including cellular adhesion/growth promotion, bio-detection and cosmetic benefits. In addition, applications of these textiles also become broadened, covering not only apparels and wound care dressings, but also biosensors, catalyst carriers, suture and tissue engineering scaffolds. Many bio-textiles have found great success in their respective applications leading to promotion of human health and improvement of life quality. This chapter will discuss types of bio-functional textiles, manufacturing methodologies of bio-functional textiles, evaluations of bio-functional effects and safety, application examples, as well as future trends in the development.

15.2 Types of bio-functional textiles

Examples of bio-functional textiles range from simplest wound care dressings, apparels, to most complicated tissue engineered scaffolds and biosensors. Here we would like to divide the discussion of different types of bio-functional textiles into two categories according to the end uses of the textiles: apparel and non-apparel usage.

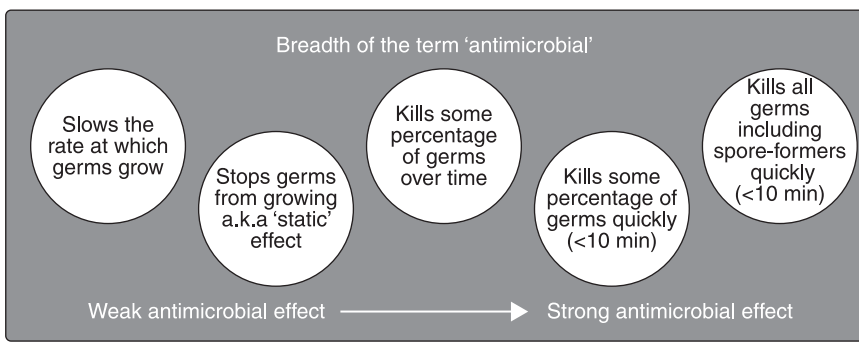
© Woodhead Publishing Limited, 2011

15.2.1 Apparel products

Antimicrobial function

Antimicrobial textiles used in apparel products are mainly adopted to curb malodor, and protect wearers from the contamination of biological agents/fluids. Antimicrobial activity can be put into a range: weakest to strongest as shown in Fig. 15.1 (Tanner, 2009). Slowing down and stopping the growth of microorganisms (biostatic), or killing some percentage of microorganisms (biocidal) over time remain at the lower end of the antimicrobial power and can be useful in controlling odors. Quaternary ammonium compounds have been used extensively in registered disinfectant and antiseptic formulations. The positive end of quaternary ammonium compounds can attract bacteria with negatively charged surface; then the long alkyl chain can penetrate into the membrane so to kill the bacteria. In solution disinfection, it was believed that the optimum alkyl chain size should be between 12 and 18. Because these compounds have a stable bacteria killing feature, scientists have tried to apply them on textile substrates (Yasuda *et al.*, 1985; Ma and Sun, 2005; Martin *et al.*, 2006; Lin *et al.*, 2003). Since quaternary ammonium compounds are not consumed by their interactions with microbes, their activities can last for the lifespan of the fabrics, and be reactivated repeatedly by laundering. Cleaning could remove the debris of bacteria or other microorganisms that covers the bioactive sites. However, it generally takes several hours to a day for textile substrates treated with quaternary ammonium compounds to show substantial reduction of the challenging microorganisms. Suitable applications are odor control in both garment fabrics and carpet fibers.

Chitosan is a linear polysaccharide composed of randomly distributed β-(1-4)-linked D-glucosamine (deacetylated unit) and *N*-acetyl-D-glucosamine (acetylated unit). It was found that chitosan could provide positive kill of microorganisms including fungi, bacteria and even viruses (Rabea *et al.*, 2003). Different



15.1 What is 'antimicrobial' (Tanner, 2009). (Reproduced with permission from Benjamin Tanner, PhD, Antimicrobial Test Laboratories.)

© Woodhead Publishing Limited, 2011

mechanisms of the antimicrobial action of chitosan have been proposed. Several studies suggested that chitosan alters cell permeability, causing leakage of proteinaceous and intracellular components (Sudarshan *et al*., 1992; Leuba and Stossel, 1985). It has also been proposed that chitosan can penetrate into the nucleus of fungi and impede RNA and protein synthesis (Hadwiger *et al*., 1985). Antimicrobial activity of chitosan is related to various factors. Chitosan is more effective in killing fungi and algae than bacteria (Savard *et al*., 2002). The shortest chitosan oligomer demonstrating effective antifungal activity contains seven residues (Kendra and Hadwiger, 1984). Studies of the impact of molecular weight on chitosan's antibacterial activity revealed that the molecular weight of chitosan should fall in the range of 10 000 to 100 000 to be bacteriostatic (Chen, 1998). Certainly, the degree of deacetylation, the concentration in solution, and the pH of the medium all influence the antibacterial activity of chitosan. Several attempts have been made to embed this polymer into textiles (Shin *et al*., 1999; Seong *et al*., 1999). The advantages of using chitosan for textile antimicrobial finish include the fact that it is not allergenic to humans, it promotes wound healing and is biodegradable (Knittel and Schollmeyer 2000). However, chitosan also needs hours to days to demonstrate a significant reduction of challenging bacteria.

Besides directly killing odor-generating bacteria, textile finishes can combat body odors through two other mechanisms: removing the odor precursor molecules upon their formation and covering up the odors with fragrances. Reactive cyclodextrins were successfully synthesized to address the odor problem via the first mechanism (Schmidt *et al*., 2003). Cyclodextrins are torus-shaped molecules with hydrophobic cavities in the range of 0.5–0.85 nm. They can store the organic molecules from sweat so that they undergo microbiological decomposition and hence the formation of malodors is prevented. On the other hand, the malodor decomposition products can also be stored and subsequently removed during laundry processes. Meanwhile, antibacterial agents have been incorporated into the cavities of cyclodextrins attached to the fabric to give the fabric antibacterial properties.

All of the above-mentioned antimicrobial compounds are suitable for odor control textiles. Nowadays, the impetus for antimicrobial finishing of textiles have gone beyond anti-odor performance. Concerns on nosocomial infections, chemical/biological protection for emergency responders and military personnel, as well as wound dressing, are new emerging reasons for the development of more effective and durable antimicrobial textiles. Textiles are susceptible to contamination by various microorganisms, and contaminated medical use textiles such as uniforms and bedding can be important sources of cross-infections. Of the 1561 nosocomial outbreaks studied, 21% have been attributed to contaminated surfaces, including textiles (Gastmeier *et al*., 2006). It was reported that certain microorganisms could survive as long as 90 days on textiles (Wendt *et al*., 1998). Since 'an ounce of prevention is worth a pound of cure', it is definitely beneficial

© Woodhead Publishing Limited, 2011

to have medical apparel products that passively combat microorganisms in order to decrease the chances of cross-infections in hospitals.

N-Halamine compounds are a group of chemicals that can demonstrate almost instantaneous kill of many germs. Biocidal functions can be conferred onto textiles by introducing *N*-halamine compounds (Sun and Sun, 2001; Liu and Sun, 2006; Liu and Sun, 2008; Liu and Sun, 2009). The highly effective elimination of bacteria (a 6 log reduction of *Escherichia coli*) can be typically achieved with a contact time of 15 minutes with only around three per cent add-on of the functional agents (Qian and Sun, 2004).

Inorganic salts, particularly silver, have been used for odor control for a number of years. Recently, there has been an explosion of interest in this field due to developments in nanotechnology (Son *et al*., 2004; Yan and Chen 2003; Kim *et al*., 2007). For example, silver nanoparticles with an average size of 8 nm were successfully immobilized onto a nylon nanofiber mat and could induce a 5 log reduction of *Escherichia coli* within two hours of contact (Dong *et al*., 2008).

Insect repellent function

In the old days, camphor balls were put in wardrobes to keep insects away from clothing made of protein fibers such as wool and silk. As outdoor activities such as forest jogging, fishing and camping become more and more popular, the need for mosquito repellent garments arose. Mosquitoes, with their pesky whining and itchy bites, annoy people. They also contribute to the transmission of certain viruses. It has been confirmed that the West Nile virus can 'jump' from birds to humans via mosquitoes. Mosquito repellent sprays are widely used to help in the battle against mosquitoes in summer. To be continually effective, most mosquito repellent formulae need to be reapplied to the skin every 30–60 minutes. Textile researchers have developed an alternative to mosquito spray: a mosquito repellent garment. Pyrethrum was extracted from chrysanthemum and applied to nylon and cotton via both padding and exhaust methods (Gopalakrishnan, 2007). The repellent finish can survive five to ten washes. β-CD has been covalently immobilized onto cotton to serve as supramolecular host for insecticide agents cypermethrin and parllethrin (Abdel-Mohdy *et al*., 2008). Compared with control samples, the cotton fabrics grafted with β-CD and loaded with insecticides showed better and more durable mosquito repellency. Even after washing, the retention percentages of the repellent action could reach 82% and 100%, respectively, for β-CD-grafted cotton fabrics treated with cypermethrin and parllethrin, as compared to 63% and 61% for control samples.

Cosmetic function

Clothing has long been expected to provide more functions than aesthetics and basic protection from weather. Recently, a new term 'cosmetic textiles' was

© Woodhead Publishing Limited, 2011

coined to refer to textiles designed to deliver bio-active agents with cosmetic benefits. The commonly used cosmetic textile agents (CTA) include lavender oil (Sohn *et al*., 2007), vitamin C (Cheng *et al*., 2009), aloe vera (Cheng *et al*., 2010) and other skin care substances. Microencapsulation techniques have been used to incorporate and control the delivery of these agents. The working mechanism involves the release and transfer of the encapsulated bio-active agents to the skin upon rubbing, moisturizing or with body heat. The major challenge lies in improving the laundry durability of the incorporated bio-functions.

15.2.2 Non-apparel products

Antimicrobial function

The major non-apparel product of antimicrobial textiles is wound care dressing. Inactivating bacteria, and hence avoiding infection, is critical in the successful management of chronic and burn wounds. Antimicrobial modification of wound care dressings is quite different from that of clothing. First, a wound dressing with antimicrobial activity should act within the wound healing environment in such a way as to minimize the cytotoxicity while maintaining its antimicrobial effectiveness. Even though *N*-halamine compounds are highly effective in inactivating infectious microorganisms, they may not be suitable for use in wound care dressings due to cytotoxicity concerns. Another major difference with antimicrobial finishes of apparels lies in that wound care dressings will not be subjected to washing so durability of the antimicrobial finish during laundering is not a concern any more. This opens doors for more choice of antimicrobial agents. Wound care dressings impregnated with leaching biocides, such as silver nanoparticles, and antibiotic gentamycin sulfate have demonstrated satisfying bactericidal activities in both *in vitro* and *in vivo* tests (Kuroyanagi *et al*., 1994). There are also reports on the application of non-leaching antibacterial agents such as a polymeric quaternary ammonium substances (Liesenfeld *et al*., 2007).

Bio-sensing textiles

Biosensors have found various applications in clinical diagnosis, in the monitoring of biological warfare agents, and in the detection of pathogenic microorganisms. A biosensor generally consists of a bio-recognizing molecule and a transducer. It is devised to selectively detect bacteria and other biological species. Sensitivities are the key for quick and accurate detection. In recent years, fibers in the nanometer size range have been researched the most for this application since they can offer huge specific surface areas for the immobilization of bio-recognition molecules. Li *et al*. (2007) achieved surface segregated biotin nanofibers using a one-step electrospinning technique. The authors envisioned its application in hospital for detection of contagious microorganisms or in food packaging for food-borne

© Woodhead Publishing Limited, 2011

diseases such as *Escherichia coli* O157. Wang *et al*. (2008) covalently bonded biotin onto the surface of nanofibers to detect straptavidin in solution which can be grouped as a catalytic biosensor. The bound biotin can still retain 40% of its original activity after being reused four times. In another report, the globular protein bovine serum albumin (BSA) was directly electrospun into nanofibers, which could be used to monitor the intracellular pH in living cells after being tagged with fluorescein isothiocyanate (FITC) (Kowalczyk *et al*., 2008). No real applications of bio-sensing fibers have been achieved at present but the potential is huge for nanofiber mats to be used as biosensors and bio-detectors.

Bio-catalytic textiles

Immobilizing enzymes onto solid substrates can enable easy purification of products from reaction mixtures as well as efficient recovery of catalytic enzymes. The catalytic activity also increases dramatically when the substrate presents huge surface areas.

Lipase is a simple enzyme with high hydrolytic activity and broad specificity. So, it is often chosen to serve as a model enzyme for the immobilization study. A sol–gel method was used to entrap lipase on cellulose acetate gel fiber with an average diameter of 500 μm (Ikeda and Kurokawam, 2002). In catalyzing the esterification of ibuprofen with propyl alcohol, the immobilized lipase demonstrated better enantioselectivity compared with crude lipase. Also, even after 15 times of repeated uses (20-h reaction/use), the immobilized lipase demonstrates similar activity and enantioselectivity as the first use. However, after the immobilization, the activity of the lipase decreased to only 10–20% of its original activity and the loading was only 25 mg lipase per gram of the fiber. Since the accessibility of entrapped enzymes in fibers is critical to their activities, nanosized fibers were spun and immobilized with enzymes. Electrospinning is a unique way to form a nanosized fiber, and activities of enzymes were not found much affected by the high electric voltage during the fiber spinning. Wang and Hsieh (2008) entrapped lipase on a PVA fiber mat and found the stored durability of the immobilized lipase increased as compared to crude lipase. Loading of the lipase up to 50% could be achieved on PVA nanofibers. The bound lipase showed similar catalytic activity as crude lipase and better storage durability. When stored at 20°C and 65% relative humidity, the immobilized lipase demonstrated eight times longer half-life than the crude lipase. The difference was even greater when the enzyme was stored at a higher temperature. However, the cross-linking of PVA in ethanol solution to achieve water insoluble PVA nanofiber mat could cause significant loss of the bioactivity of the incorporated lipase.

Physical adsorption is another commonly adopted approach to immobilize enzymes on fibers. Glycidyl methacrylate (GMA) grafted polyethylene hollow fibers, after further modification with diethylamine, were found to adsorb 0.49 g of bovine serum albumin (BSA) per gram of the modified fibers (Tsuneda *et al*.,

© Woodhead Publishing Limited, 2011

1995). Adsorption of lipase on polyacrylic acid grafted cellulose nanofibers can be achieved at 1.28 g/g fiber (Chen and Hsieh, 2005). However, the activity of the immobilized lipase is only two to nine per cent that of the crude lipase due to the decreased conformational freedom and accessibility of the immobilized lipase.

Textiles as carriers for drug/protein/nutrient delivery

For biomedical applications of textiles as tissue scaffolds and wound care dressings, the delivery of drugs/nutrients/proteins is often a necessary function. Many nutrients, drugs and proteins, including epithelial growth factor (EGF), platelet derived growth factor (PDGF), fibroblast growth factor (FGF), vitamins A, C and E, zinc, and copper minerals have been added into textiles for controlled delivery. Mostly, the electrospinning technique was adopted to encapsulate bioactive agents into nanofibers since this technique possesses many advantages, including that it could be applied for a wide range of pharmaceutical compounds either functionalized or non-functionalized; and it could be used for more than one drug at the same time. In addition, more than one polymer could be used to be electrospun at one jet at the same time. More importantly, it has been confirmed by many studies that enzymes and even DNAs are not denatured when exposed to high voltage during the electrospinning process (Wang and Hsieh, 2008; Luu *et al*., 2003).

The simplest route of encapsulating pharmaceutical compounds into nanofibers is that drugs or proteins are mixed with polymers in a common solvent and then electrospun into bio-functional nanofibers. More than one drug could be encapsulated into a nanofiber via one-pot electrospinning. Four types of non-steroidal anti-inflammatory drugs were added into cellulose acetate acetone/DMAc solution and electrospun into smooth nanofibers with an average diameter of 231 nm (Tungprapa *et al*., 2007). The drug loading percentage was as high as 20% by weight and no drug crystal was found on the surface of the nanofiber, in contrast to their film counterparts where there were many drug crystals on the surface resulting from burst release. Also, as confirmed by ^{1}H NMR, the chemical natures of all encapsulated drugs had not changed before and after the electrospinning. Compared with drug-loaded film counterparts, drug release from drug-loaded nanofiber mats was much quicker, and maximum amount of the drugs released was much greater. When it is difficult to find a co-solvent for polymeric substrates and drugs, emulsion electrospinning can be used (Xu *et al*., 2008). Besides electrospinning of drug emulsions, a co-axial set-up is another effective way to achieve core-shell structured nanofibers for controlled release of the encapsulated bio-active agents. The release saturation of nanofiber-encapsulated bioactive agents was reported by many studies as being well below 100%, suggesting solid-state diffusion was not the leading mechanism of release. Srikar proposed that desorption of encapsulated bioactive agents from the nanopore surfaces of electrospun nanofibers is the rate-limiting release stage

© Woodhead Publishing Limited, 2011

(Srikar *et al*., 2008). Generally speaking, the value of the desorption enthalpy, E, determines the duration of the release process, and the ultimate release level is related to the nanoporosity factor, α.

Besides drugs/proteins, some natural polymers can also offer other biological functions such as biodegradability, biocompatibility, and wound healing activity. Many bioactive natural materials could be directly spun into fibers to serve as wound dressing or tissue engineering scaffolds. Dibutyrylchitin (DBC), an ester derivative of a natural polysaccharide, chitin, was blended with poly(1-caprolactone) and wet-spun into fibers with good mechanic strength (Schoukens and Kiekens, 2009). Used as a dressing for burn wounds, the fibers made of DBC were believed to deliver butyrate, which was found to be the dominant energy source for epithelial cells and improve wound healing to burn wounds. A preliminary clinical trial involving ten patients with burn wounds demonstrated that the DBC dressing promoted burn healing. The derivatization of chitin served two functions: (i) increased the solubility of chitin in solvents so to enable fiber spinning; and (ii) provided a way to immobilize butyrate for delivery in wound sites. It was also reported that even without releasing any bioactive agents, biodegradable fibrous scaffolds would facilitate the growth of normal skin since the skin cells could be guided for self-repair. Zhang *et al*. (2005) pioneered the work of aligning nanofibers to guide the growth of smooth muscle cells (SMCs). *In vitro* tests demonstrated that SMCs adhered and proliferated much better on aligned nanofibrous scaffold than on polymer films.

15.3 Evaluation of bio-functional effects and safety

Antimicrobial property is one of the most important bio-functions for textiles. Two major test protocols are widely employed: the agar diffusion test (such as AATCC Test Method 147 (AATCC, 2010b)) and the suspension test (challenge test), such as AATCC Test Method 100 (AATCC, 2010a), ASTM E2149-10 (ASTM international, 2010) and JIS L 1902 (JIS, 2008).

AATCC Test Method 147 is a qualitative method which offers a quick differentiation between active (clear zone of growth inhibition around the test specimen) and passive antimicrobial activities (no zone of inhibition). All other methods mentioned above are quantitative test methods. As required in ASTM E2149, fabrics should be immersed in a large volume of non-nutritive liquid and shaken for a predetermined period of time. It may not be very realistic since this situation rarely happens in real life. JIS L 1902 is quite similar to AATCC Test Method 100. A diluted suspension of microorganisms is placed on test specimens. Microbial concentrations on the fabrics are then enumerated after the contact period. Major differences between JIS L 1902 and AATCC Test Method 100 include: a much less nutritive microbial inoculum is used in JIS L1902 and three replicates are required in JIS L 1902 whereas only a simple replicate of the test is performed according to AATCC Test Method 100. One noteworthy point is that

© Woodhead Publishing Limited, 2011

reductions of dried microbial inocula on fabrics may not be as large as results obtained from tests performed according to JIS L 1902 and AATCC Test Method 100, since fabrics are kept wet during the tests and antimicrobial agents generally work better in the presence of liquid. AATCC 147-2004 and AATCC 100-2004 specify two bacteria *Klebsiella pneumoniae* (ATCC No. 4325) and *Staphylococcus aureus* (ATCC No. 6538) as test organisms. A recently published article highlights challenging textiles having odor reduction claim with these species prevalence on axillary skin, such as *Corynebacterium* sp. CDC G5840 and *C*. m*ucifaciens* sp. DMMZ 2278 (McQueen *et al*., 2010). A foot odor associated bacterium *Bacillus licheniformis* was found to be resistant to three out of four commercially available antimicrobial fabrics tested.

For the bio-functional textiles used in intimate contact with human skin, biological safety tests on cytotoxicity, hemolysis, sensitization and irritation should be carried out. *In vitro* cytotoxicity tests, *in vitro* hemolysis tests and *in vitro* sensitization tests can be conducted following ISO 10993-5:1999 (ISO, 1999), ISO 10993-4: 2002 (ISO, 2002a) and ISO 10993-10: 2002 (ISO, 2002b). Detection of membrane irritants is generally carried out using the Draize *in vivo* rabbit eye test (Draize *et al*., 1944). In the past 20 years, due to the trend of reducing, refining and replacing animal experiments, chicken-embryo models have been developed for testing embryotoxicity as an alternative to the Draize test (Luepke, 1985; Luepke and Kemper, 1985). The hen's egg test (HET) and the HET–chorioallantoic membrane test (HET-CAM test) are two well-known chicken-embryo models. A good correlation between HET-CAM assessments and reported data based on Draize eye tests have been reported (Luepke, 1985b).

Besides the tests of bio-functions and bio-safety, physiological comfort test of bio-functional textiles has also attracted interest. Bartels tested the thermophysiological and skin sensorial wear comfort of biofunctional textiles using a skin model and a skin sensorial test apparatus (Bartels, 2006).

15.4 Applications of bio-functional textiles

Some applications for bio-functional textiles have been discussed in previous sections. This section will focus on the commercially available bio-functional textiles.

15.4.1 Mosquito repellent (MR) garments

As mentioned before, mosquitoes not only annoy people with their itchy bites but they also transmit diseases to people. While biologists and chemists are trying to control mosquito reproduction and develop new effective and safe repellents, textile researchers are working hard to incorporate these new repellents into textiles for safe and long-lasting personal protection. However, this is a market

© Woodhead Publishing Limited, 2011

with high entry barriers since MR textiles are regulated by the U.S. Environmental Protection Agency (EPA) through which very rigorous standards have to be met implicating lengthy application process and large upfront investments. So far, Insect Shield LLC is the only US company whose insect-repellent apparel has been granted EPA registration. From 1997, researchers at Insect Shield started research on MR garments, and registration of its insect-repellent apparel by EPA was only achieved in 2003. Insect Shield MR apparels are already available from various outdoor brands such as ExOfficio, Tilley, L. L. Bean, Orvis and Ariat.

According to Insect Shield's claims, its odorless and invisible insect protection can last 70 launderings. The active ingredient in its MR garments is permethrin, which is a type of pyrethroid which functions as a neurotoxin to the mosquito, has low mammalian toxicity and poor absorbance by human skin. Bonded onto textiles using the Insect Shield's patent-pending process, the MR products can be handled as other apparels for bleaching and pressing, with only the exception of dry cleaning.

15.4.2 Antibacterial wound care dressings

Smith & Nephew, the UK's largest medical device company, has been in the market for over 150 years. It is the second largest organization in advanced wound management, and its wound care dressing product Acticoat (nanocrystalline silver dressing) has been used extensively by researchers for comparative *in vitro* and *in vivo* studies (Wright *et al*., 1998; Thomas and McCubbin, 2003; Dowsett, 2003). Among four dressings tested in an *in vitro* study (Thomas and McCubbin, 2003), Acticoat demonstrated the quickest antimicrobial effect against three micro-organisms: *Staphylococcus aureus*, *Escherichia coli* and *Candida albicans*. The rapid action of the dressing was explained as a result of an equilibrium-driven release of silver ions from the dressing. This is closely related to the way Acticoat is manufactured. Acticoat is made by using a physical vapor deposition technique. In a vacuum chamber filled with argon gas (as an anode), argon ions are generated when an electric current is passed. The silver atoms are then knocked out by the argon ions to coat the substrate in the form of nanocrystals each measuring 15 nm across. Those silver nanocrystals serve as a source for ample amounts of silver ions during the application.

Clinical evaluations also provided evidence of the effective use of Acticoat dressings in chronic wounds. For example, the effectiveness of Acticoat was evaluated on a variety of chronic non-healing wounds, including foot ulcers, venous stasis ulcers, pressure ulcers and miscellaneous wounds in 29 patients (Sibbald *et al*., 2001). All patients showed a decrease in exudate levels and several patients had a dramatic decrease in pain. The study concluded that a dramatic clinical improvement was achieved by using Acticoat on those wounds studied.

© Woodhead Publishing Limited, 2011

15.4.3 Cosmetic textiles

Textiles have long been termed as 'second skin'. Recently, a new category of functional textile capable of delivering cosmetic benefits has attracted much interest, and a new term, 'cosmetic textile', has been coined. The functioning principle is that cosmetic agents such as skin moisturizing substances can diffuse from apparel onto the skin through contact generated by the natural movement of body. Contact causing friction, pressure, change of temperature, or biodegradation of the shell polymer can facilitate the release of the core content so to gradually refresh the skin.

Several companies are marketing their cosmetic textile related products. A textile company headquartered in Germany, Cognis, supplies the textile industry with chemical solutions to making cosmetic textiles. Many bioactive ingredients including menthol, vitamin E, passion fruit oil, valerian, amber tree resin oil and lavender are encapsulated into their chitosan-based microcapsules, which is sold under the trademark Skintex®. The microcapsule could be coated onto any textile substrates using the conventional exhaustion-dry process. It is claimed that the bio-function can survive after several washes as long as the care instructions are followed. Skintex® finished textiles could deliver various bio-functions. For example, bio-active ingredients like menthol, orange, ginger, or rosemary can be incorporated into bathrobes to deliver aroma as revitalizing aromatherapy.

An India-based company, Americos Industries Inc., is marketing Americos microcapsules for textile finishing. The microcapsules are incorporated with Biocap Aloe Vera or vitamin E for moisturizing benefits and can be applied onto textiles using pad-dry and exhausting processes.

15.5 Manufacturing of bio-functional textiles

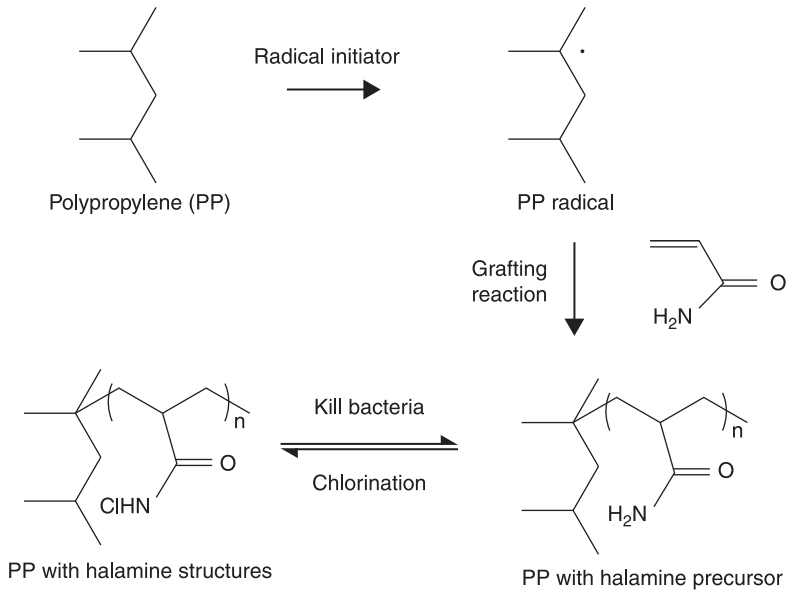
Both physical and chemical methods have been adopted to impart bio-functions to textiles. Advancements in polymer surface modification and fiber fabrication techniques open up new possibilities for encapsulating bio-active agents – even cells – into textile materials. The following section will cover the application of these advancements in manufacturing bio-functional textiles.

15.5.1 Incorporation of bio-functional additives before formation of fibers

In general, the advantages of this modification method include that the resulting bio-functions will be quite durable, and it is a one pot or one step process. The drawbacks are low flexibility of the process and only applicable to manufactured fibers.

For example, *N*-halamine precursors were incorporated into polypropylene (PP) fibers through melt spinning (Badrossamay and Sun, 2009). The reaction scheme is shown in Fig. 15.2. In order to expose more active agent to surface, a new melt-spinning process was adopted for fabricating PP micron-sized fibers

© Woodhead Publishing Limited, 2011



15.2 Grafting acyclic halamine moieties to polypropylene.

(Wang *et al*., 2007). PP grafted with *N*-halamine precursor moieties was blended with cellulose acetate butyrate (CAB) and melt extruded into random sea-island composite fibers. PP fibers in the diameter range of several hundred nanometers to a few micrometers were obtained following removal of CAB with acetone. After chlorination, the modified PP nano- or submicron-size fibers exhibited potent antibacterial activity against *Escherichia coli*. For example, 2,4-diamino-6-diallylamino-1,3,5-triazine (NDAM) grafted PP microfiber could bring 100% reduction of 10^5–10^6 CFU/ml *Escherichia coli* within one hour of contact. This spinning method makes use of phase separation between two thermodynamically immiscible polymers to fabricate micron- and/or nanosized fibers and entails no complex design of special spinneret (Wang *et al*., 2007). Compared with other nanofiber fabrication methods such as electrospinning or sea-island spinning, it has such advantages as high productivity, rapid and simple extrusion devices. Electrospinning is a common process for making bio-active nanofibers. Many bio-active agents including bacteria and DNAs have been added into polymer solution and then electrospun into functionalized nanofibers. There were reported efforts for enriching functional agents onto the surface of formed nanofibers (Sun *et al*., 2007). The electric field used in electrospinning was proven to be able to promote surface segregation of two polarizable bioorganic peptide segments (Ser-Glu-Glu)$_3$ (SEE)$_3$) and Ac-(Ser-Glu-Glu)$_3$Lys. Specifically, PEO was first coupled with (SEE)$_3$ to form a PEO–peptide conjugate. Then, the PEO–peptide conjugate was added in the aqueous PEO solution and electrospun into nanofibers. The length of PEO chain was judiciously designed to allow both easy diffusion of the

© Woodhead Publishing Limited, 2011

conjugate during electrospinning and co-crystallization with the PEO matrix for durable anchoring of the conjugate on the nanofiber surface. Not like convergent isofield lines existing in conventional electrospinning setting, in these reports, an electric field with parallel isofield lines was generated between a planar cathode (behind the needle) and the collection anode.

15.5.2 Coating (post-physicochemical finishing)

Traditional coating methods used in textile industry include pad-dry-cure, knife coating and exhaustion-dry processes. These methods are universally applicable and have been used extensively to impart bio-functions to essentially all textile substrates. Copolymers poly(vinyl acetate-*co*-methacrylamide) and poly(vinyl acetate-*co*-acrylamide) were coated onto PET films and fabrics via the exhaustion-dry process. After chlorination, both the modified PET films and fabrics could bring a 6 log reduction of *Escherichia coli* and *Staphylococcus aureus* within one to five minutes contact (Ren *et al*., 2010). Similarly, two *N*-halamine siloxane precursors, 5,5-dimethyl-3-(30-triethoxysilylpropyl) hydantoin and 3-(30-triethoxysilylpropyl)-7,7,9,9-tetramethyl-1,3,8-triazaspiro[4.5]-decane-2,4-dione, were coated onto PET fabric via an exhaustion-dry process. After activation by chlorine bleach, the coated PET fabrics were challenged by *Staphylococcus aureus* and *Escherichia coli*. A 6.8 log reduction of *Staphylococcus aureus* and a 6.97 log reduction of *Escherichia coli* were achieved within 5 and 30 minutes of contact, respectively.

ZnO nanoparticles with an average size of 38 nm were impregnated onto cotton fabrics using the pad-dry-cure method (Vigneshwaran *et al*., 2006). Effective inactivation (>90% reduction) of *Staphylococcus aureus* (Gram positive) and *Klebsiella pneumoniae* (Gram negative) was achieved after 24-hour contact. In another study, the padding solution was formulated with ZnO powder, an appropriate binder and a dispersing agent (El-Naggar *et al*., 2003). Both cotton and cotton/PET fabrics were padded through the above ZnO formulation and either cured at 160°C or exposed to cobalt-60 gamma irradiation. The ZnO formulation formed a thin layer of coating on fabrics after gamma irradiation or thermal processing. The microbial resistance of the ZnO coated fabrics was greatly improved, as evidenced from the results of a soil burial test.

Recently, a sonochemical method was successfully applied for coating cotton fabrics with metal oxides (Perelshtein *et al*., 2010). Ultrasonic irradiation was used to deposit MgO and Al_2O_3 nanoparticles onto surfaces of cotton fabrics. Briefly, a cotton bandage was immersed in a MgO/Al_2O_3 nanoparticle ethanol/ethylene glycol dispersion in a sonication flask and then irradiated for two hours with a high-intensity ultrasonic horn. Around one per cent of nano-oxides could be deposited and the resulting MgO nanoparticle coated cotton fabrics demonstrate strong antibacterial activity (>90% reduction of both *Escherichia coli* and

© Woodhead Publishing Limited, 2011

Staphylococcus aureus within one hour of contact). More importantly, the sonochemical process holds the potential to be scaled up for larger dimensions.

Layer-by-layer (LBL) assembly is a simple, versatile, and inexpensive coating approach by which polyelectrolytes with opposite charges are sequentially adsorbed onto macroscopically flat or non-planar (e.g. colloidal core-shell particles) surfaces. Compared with other available assembly methods, LBL assembly is simpler and more universal and allows more precise thickness control at the nanoscale. The LBL electrostatic approach has been successfully used in assembling enzyme proteins onto fiber surfaces (Xing *et al*., 2007). To achieve a uniform coating, three precursor polyelectrolyte layers of poly(dimethyldiallyl ammonium chloride) (PDDA)/sodium poly(styrene sulfonate) (PSS)/PDDA were deposited onto cotton fiber. Following that, the enzyme laccase and PDDA were alternately deposited with an outmost enzyme layer. It was found that the enzymatic activity increased linearly with the enzyme layering.

In application of LBL or other coating methods that are taking advantage of electrostatic interactions, the substrate needs to carry charges to enable the assembly. Lu and Hsieh (2010) covalently bonded active dye CB (negatively charged) onto cellulose nanofibers and then carried out LBL assembly of lipase/CB bilayers. Dong *et al*. (2008) deposited silver nanoparticles onto the surface of electrospun nylon nanofiber by adjusting pH of the coating solution to enable a dimeric association involving two hydrogen bonds between a group of nylon nanofiber and carboxylic acid group of the citric acid/nanoparticle complex. The Nylon 6 nanofiber mat coated with Ag nanoparticles could bring total kill of *Escherichia coli* within two hours of contact.

Most recently, the techniques commonly used in processing inorganic materials such as ceramic and metal have been successfully applied in textile surface treatment. The sol–gel process is one of them. This process is a wet-chemical technique which has long been used for the fabrication of glassy and ceramic materials. In this process, metal alkoxides or metal chlorides dispersion solution (sol) undergoes hydrolysis and polycondensation reactions to form a colloid. Eventually, the sol turns into an inorganic network containing a liquid phase (gel). A subsequent drying process removes the solvent from the gel, generating a micro-porous metal oxide matrix. This porous matrix allows the incorporation of homogeneously bioactive compounds, biomolecules and even whole living cells into metal oxide matrices (Livage *et al*., 2001; Bottcher *et al*., 2004).

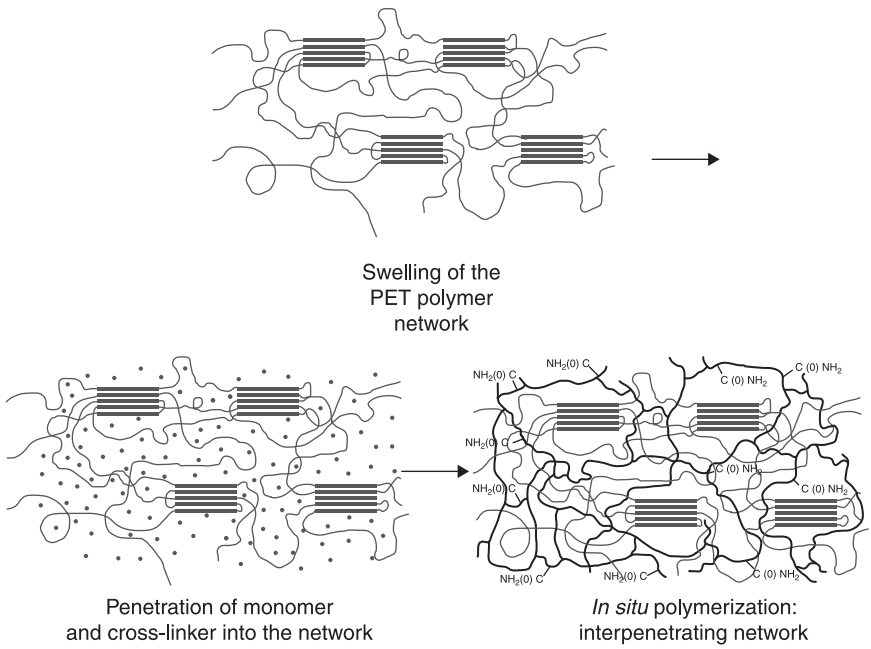
Chemical vapor deposition (CVD) is a chemical process used to produce high-purity, high-performance coating on solid materials. The process is often used in the semiconductor industry to produce thin films. In a typical CVD process, the substrate (such as wafer) is exposed to one or more volatile precursors, which react and/or decompose on the substrate surface to produce the desired deposit. The high temperature nature limits its application in thermally labile textile substrates. Creatively, Lewis designed a new vapor deposition method based on hot filament CVD, which is called initiated CVD (iCVD) (Lewis *et al*., 2001).

© Woodhead Publishing Limited, 2011

Superhydrophobic poly(caprolactone) fibers can be generated by deposition of fluoropolymer using this method (Ma *et al*., 2005). Even though there is no report of bio-functionalized of textiles using this method. It possesses a great potential to impart textiles with new bio-functions.

15.5.3 Surface modification via the formation of an interpenetrating network

In recent years, the formation of surface interpenetrating network (IPN) polymers has emerged as a viable alternative to synthetic grafting techniques in upgrading the properties of thermoplastic semicrystalline polymers like poly(ethylene terephthalate) (PET) (Liu *et al*., 2010; Rudenja *et al*., 2010; Zhao *et al*., 2010). Formation of IPNs was conventionally used to fabricate new composite materials for such applications as construction materials, voice insulation, damping materials. Liu's group successfully immobilized polyamides including polyacrylamide (PAM) and polymethacrylamide (PMAM) onto PET by forming an interpenetrating network (IPN), the process of which is illustrated in Fig. 15.3



15.3 Formation of thermoplastic semi-interpenetrating network.[77] (Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission). Black dots represent monomer acylamide (AM) or methacrylamide (MAM) and cross-linker *N,N'*-methylenebisacrylamide (MBA). Black lines represent cross-linked poly(acrylamide) or poly(methacrylamide).

© Woodhead Publishing Limited, 2011

(Liu *et al*., 2010). The diffusion of acrylamide (AM) (or methacrylamide (MAM)), divinyl cross-linker *N*,*N*'-methylenebisacrylamide (MBA) and photoinitiator benzophenone (BP) into the PET substrate was facilitated by swelling in a mutual solvent, which expanded the structure of PET and made it more receptive to the penetration of monomers, preferably on a site of amorphous phase of PET. The diffused monomer and cross-linker were then copolymerized by ultraviolet irradiation, interlocking the chains of both polymers into a novel hybridized structure. The so-immobilized polyacrylamide (PAM) was durable against Soxhlet extraction with both distilled water and methanol, and it could be converted to acyclic *N*-halamine which has been proven to be an effective biocide (Liu and Sun, 2006; Liu and Sun, 2008; Liu and Sun, 2009; Ren *et al*., 2010). A new term, 'thermoplastic semi-IPN', has been coined to describe such an IPN. It is named as such because the substrate-thermoplastic PET is physically cross-linked, while the immobilized functional polymer is chemically cross-linked to physically interlock with the substrate polymer. Thermoplastic IPN involves only physical cross-links (crystalline areas serve as cross-linking point); in semi-IPN, one linear or branched polymer is blended with another chemically cross-linked polymer network. Neither of the two definitions fits this situation so two descriptors, 'thermoplastic' and 'semi', are combined to reflect the similarity between the synthesis of this structure and the other two IPNs. Advantages of this new technique include no damage to the base substrate, high immobilization densities, mild reaction conditions, and chemical stability of the modified interface due to its resistance to mechanical attrition. This method is not grouped into coating method because the functional polymer actually penetrates into the textile substrate, and there is an interpenetrating interface of substantial thickness rather than a superficial coating.

15.5.4 Chemical method

In a general sense, chemical and physicochemical coating methods have complementary advantages. As far as comfort and durability towards laundry and abrasion are concerned, chemical methods outweigh its counterparts. Chemical methods of creating bio-functional textiles include grafting polymerization, covalent bond formation and ion-exchange/chelation. Covalent bond formation is restricted in certain natural and regenerated fibers such as cotton, wool and viscose. And, due to the heterogeneous nature of graft reactions, only those highly reactive reagents such as aldehyde, halogenated alkyl compound, epoxide, acyl chloride etc could be used for covalent modification.

Cyclodextrins (CDs) are cyclic oligosaccharides composed of five or more α-D-glucopyranoside units linked together by 1,4-glycosidic bonds. They have a toroid structure with different cavity volumes and can form inclusion complex with various guest molecules, drugs or other bioactive agents, into their hydrophobic cavity. Once immobilized onto fibrous substrates, CDs can serve as 'sockets' for various bio-active agents to achieve controlled delivery of biofunctions. Aryl

© Woodhead Publishing Limited, 2011

nitrene, converted from aryl azide under UV irradiation, is highly reactive and can undergo such reaction as insertion into C–H and N–H bonds, addition to double bonds, and proton-abstraction reactions. In one study, β-CD linked with an aryl azide moiety was immobilized onto cellulose diacetate fibers through insertion reactions initiated by UV irradiation (Park *et al*., 2009). The immobilized β-CD could form inclusion complex with a model compound, coumarin 6, as evidenced by the fluorescent micrographs. The authors foresaw biomedical applications of the β-CD immobilized cellulose fibers such as encapsulation of drugs. 2,4,6-Trichloro-1,3,5-triazine has long been adopted to serve as a bridge to covalently link dyes onto cellulose fiber. The β-CD derivative monochlorotriazinyl β-CD, which is capable of forming covalent bonding with cellulose, has been synthesized and immobilized onto cellulosic fabrics (Abdel-halim *et al*., 2010; Wang and Cai, 2008; Hebeish *et al*., 2008). Either an antibacterial (Abdel-halim *et al*., 2010; Wang and Cai, 2008) or an insect repellent agent (Hebeish *et al*., 2008) was loaded into the CD immobilized cotton fabric to achieve durable biofunctions.

In recent years, the scientific literature has revealed a growing interest in graft polymerization on textiles as a means of allowing modification of their physical and/or chemical structures. It offers a versatile means of providing both natural/regenerated and synthetic fibers with new functionalities such as biocompatibility, anti-fouling and anti-bacterial activities. In principle, there are two methods for producing grafted substrate polymers: direct coupling reaction of existing polymeric chains to the substrate polymers (grafting to) and graft polymerization of monomers to the surface (grafting from). One example of the 'grafting to' technique application in textile modification is the preparation of acyl chloride of anionically polymerized and carboxyl-terminated polystyrene for the esterification of alkali cellulose by the terminated polymeric chains (Avny and Schwenker, 1967). Accurate control of the length of the attached polystyrene chains is the advantage of this approach. However, diffusion problems entail long reaction time (24 h). And, more importantly, the functional groups must already exist in the target substrates. So, the 'grafting from' technique (hereinafter simply denoted as graft polymerization) will be focused on in the following discussion.

Both chemical initiation and radiation methods (e.g. UV, gamma rays, plasma) have been applied to initiate graft polymerization. For the case of chemical initiation, the commonly accepted mechanism involves the equations [15.1] to [15.4]:

$$I_2 \rightarrow 2I^{\bullet} \qquad [15.1]$$

$$2I^{\bullet} + \text{Tex–H} \rightarrow \text{Tex}^{\bullet} + \text{I–H} \qquad [15.2]$$

$$\text{Tex}^{\bullet} + \text{M} \rightarrow \text{Tex–M} \qquad [15.3]$$

$$I^{\bullet} + \text{M} \rightarrow \text{I–M} \qquad [15.4]$$

where $I^{\bullet}$ is the primary radical, Tex–H is the textile polymer backbone and M is the functional monomer. The relative reaction rates of equations [15.2] and [15.3], in

© Woodhead Publishing Limited, 2011

competition with equation [15.4], are of crucial importance to successful grafting reactions. This entails a cautious selection of the initiating systems. Those initiators which can decompose to generate radicals with higher propensity to abstracting hydrogen than adding to double bond should be chosen for the grafting modification.

For grafting reactions of cellulose and its derivatives, initiation by Ce^{IV} salts is probably one of the most extensively researched (Nevell and Zeronian, 1985; Leza *et al*., 1991; McDowall *et al*., 1984). First, a ceric ion is allowed to form a complex with an anhydroglucose unit, which is followed by an electron transfer within the complex. Subsequently, the C3–C4 bond of the glucopyranoid ring is broken and cellulosic radicals are formed. A quite high grafting efficiency in excess of 92% (at grafting yields of around 40%) of acrylic acid onto rayon monofilaments has been reported by McDowall *et al*. (1982). However, the need of immobilizing Ce^{IV} ion onto rayon monofilaments and reducing its concentration in grafting solution entails the use of organic solvent toluene. The required use of toxic organic solvents is a serious drawback.

Pre-embedment of macroinitiators onto thermoplastic polymers can also improve grafting efficiency. Bergbreiter developed an approach involving physical entrapment of terminally functionalized ethylene oligomers into a host polyethylene film (Bergbreiter *et al*., 1993). Pretreatments of polyester and polyethylene have also been done to increase grafting specification. Poly(ethylene terephthalate) (PET) was activated by thermal pretreatment in air or ozone to form macromeric hydroperoxides in the polymer backbone (Korshak *et al*., 1962). Thermal decomposition of the macromeric hydroperoxides in the presence of monomers will initiate grafting polymerization. Benzophenone was used to generate and mask macromolecular radicals in polyethylene film under UV irradiation (Yamamoto, 2002). Again, in the presence of monomer, macromolecular radical was re-generated under UV irradiation and grafting was initiated. Liu *et al*. (2010) adopted an interesting method to increase the efficiency of grafting polymerization. Polyamide 6,6 fabric was colored with an acid dye, anthraquinone-2-sulfonate sodium, which can also serve as a photo-initiator. Following the immobilization of the photo-initiator via ionic bonding, photo-initiated grafting polymerization of acrylic acid onto the fabric was carried out. Upon UVA irradiation, the Norrish Type II photo-initiator anthraquinone-2-sulfonate sodium was excited to preferentially abstract hydrogen from spatially close polyamide 6,6 chains, generating macromolecular radicals on the polymer substrate. Hence, polyacrylic acid was grafted onto polyamide 6,6 fabric with minimal formation of polyacrylic acid homopolymer. This technique could be used to impart antimicrobial function and other bio-functions to textile substrates.

15.6 Future trends

Bio-functional textiles cover a broad range of applications from apparel to non-apparel, including self-disinfecting surgical gown, mosquito repellent garments,

© Woodhead Publishing Limited, 2011

sutures and wound care dressings. It is a fast growing scientific field which has been and will continue to be fueled by the needs of health promotion and life quality improvement.

This is also an interdisciplinary research field which requires close collaborations among polymer and fiber scientists, physicists and biologists. For example, the understanding of the cellular and biochemical mechanisms of non-healing chronic wounds could give a platform for advances in fiber dressing design that are critically needed for optimized bioactive agent delivery and restoration of wound healing environments. New breakthroughs in fiber fabrication and surface modification techniques will enable the development of textiles with multiple and responsive bio-functions, which might be the trend for years to come.

15.7 Sources of further information

Hipler, U-C., Elsner, P. *Biofunctional Textiles and the Skin*. Karger: Basel, 2006.

Williams, R. *Surface Modification of Biomaterials: Methods Analysis and Applications*. Woodhead Publishing Limited: Cambridge, 2010.

15.8 References

AATCC (2010a). 'Antibacterial finishes on textile materials: assessment of, AATCC Test Method 100', *AATCC Tech Manual*, 85, 142–144.

AATCC (2010b). 'Antibacterial activity assessment of textile materials: Parallel Streak Method, AATCC Test Method 147', *AATCC Tech Manual*, 85, 251–252.

Abdel-halim E S, Fouda M M G, Hamdy I, Abdel-Mohdy F A and Ei-Sawy S M (2010). 'Incorporation of chlorohexidin diacetate into cotton fabrics grafted with glycidyl methacrylate and cyclodextrin', *Carbohydr Polym*, 79, 47–53.

Abdel-Mohdy F A, Fouda M M G, Rehan M F and Aly A S (2008). 'Repellency of controlled-release treated cotton fabrics based on cypermethrin and prallethrin', *Carbohydr Polym*, 73, 92–97.

ASTM International (2010). 'Standard test method for determining the antimicrobial activity of immobilized antimicrobial agents under dynamic contact conditions, ASTM E2149-10', *Annual Book of ASTM standards*, 11.05.

Avny Y and Schwenker R F (1967). 'Grafting of preformed polystyrene onto cotton cellulose', *Textile Res J*, 37, 817–823.

Badrossamay M R and Sun G (2009). 'Durable and rechargeable biocidal polypropylene polymers and fibers prepared by using reactive extrusion', *J Biomed Mater Res Part B*, 89, 93–101.

Bartels V T (2006). 'Physiological comfort of biofunctional textiles', *Curr Problem Dermatol*, 33, 51–66.

Bergbreiter D E, Srinivas B and Gray H N (1993). 'Surface graft polymerization on polyethylene using macroinitiators', *Macromolecules*, 26, 3245–3246.

Bottcher H, Soltmann U, Mertig M and Pompe W (2004). 'Biocers: ceramics with incorporated microorganisms for biocatalytic, biosorptive and functional materials development', *J Mater Chem*, 14, 2176–2188.

Chen H and Hsieh Y L (2005). 'Enzyme immobilization on ultrafine cellulose fibers via poly(acrylic acid) electrolyte grafts', *Biotechnol Bioeng*, 90, 405–13.

© Woodhead Publishing Limited, 2011

Chen T (1998). 'The relationship between specific properties and use of chitosan', presented on the National Symposium on Nature Marine Product and Nature Biological Medicine: Beijing, China, pp. 282–284.

Cheng S Y, Yuen M C W, Kan C W, Cheuk K K L, Chui C H and Lam K H (2009). 'Cosmetic textiles with biological benefits: gelatin microcapsules containing vitamin C', *Int J Mol Med*, 24, 411–419.

Cheng S Y, Yuen C W M, Kan C W, Cheuk K K L and Tang J C O (2010). 'Systematic characterization of cosmetic textiles', *Textile Res J*, 80, 524–536.

Dong H, Wang D, Sun G and Hinestroza J P (2008). 'Assembly of metal nanoparticles on electrospun Nylon 6 nanofibers by control of interfacial hydrogen-bonding interactions', *Chem Mater*, 20, 6627–6632.

Dowsett C (2003). 'An overview of Acticoat dressing in wound management', *Br J Nurs*, 12, S44–S49.

Draize J H, Woodard G and Calvery H O (1944). 'Methods for the study of irritation and toxicity of substances applied topically to the skin and mucous membranes', *J Pharmacol Exp Ther*, 82, 377–390.

El-Naggar A M, Zohdy M H, Hassan M S and Khalil E M (2003). 'Antimicrobial protection of cotton and cotton/polyester fabrics by radiation and thermal treatments. I. Effect of ZnO formulation on the mechanical and dyeing properties', *J Appl Polymr Sci*, 88, 1129–1137.

Gastmeier P, Stamm-Balderjahn S, Hansen S, Zuschneid I, Sohr D, *et al.* (2006). 'Where should one search when confronted with outbreaks of nosocomial infection?', *Am J Infect Control*, 34, 603–5.

Gopalakrishnan D (2007). 'Mosquito repellent fabrics', *Man-made Textiles India*, 50, 15–18.

Hadwiger L A, Kendra D F, Fristensky B W and Wagoner W (1985). 'Chitosan both activates genes in plants and inhibits RNA synthesis in fungi', In *Chitin in Nature and Technology*, Muzzarelli R A A, Jeuniaux C and Gooday G W (eds.), Plenum Press, New York, p. 209.

Hebeish A, Fouda M M G, Hamdy I, Ei-Sawy S M and Abdel-Mohdy F A (2008). 'Preparation of durable insect repellent cotton fabric: Limonene as insecticide', *Carbohydr Polym*, 74, 268–273.

Ikeda Y and Kurokawam Y (2002). 'Enantioselective esterification of racemic ibuprofen in isooctane by immobilized lipase on cellulose acetate–titanium *iso*-propoxide gel fiber', *J Biosci Bioeng*, 93, 98–100.

ISO (1999). 'ISO 10993-5: biological evaluation of medical devices: tests for cytotoxicity: in vitro methods', International Organization for Standardization, Geneva, Switzerland.

ISO (2002a). 'ISO 10993-4: biological evaluation of medical devices: selection of tests for interactions with blood', International Organization for Standardization, Geneva, Switzerland.

ISO (2002b). 'ISO 10993-10: biological evaluation of medical devices: tests for sensitization', International Organization for Standardization, Geneva, Switzerland.

JIS (2008). 'Testing for antibacterial activity and efficacy on textile products, JIS L 1902:2008', Japanese Standards Association, Akasaka Minato-ku, Tokyo, Japan.

Kendra D F and Hadwiger L A (1984). 'Characterization of the smallest chitosan oligomer that is maximally antifungal to fusarium-solani and elicits pisatin formation in pisum-sativum', *Exp Mycol*, 8, 276–281.

© Woodhead Publishing Limited, 2011

Kim Y H, Lee D K, Cha H G, Kim C W and Kang Y S (2007). 'Synthesis and characterization of antibacterial Ag-SiO2 nanocomposite', *J Phys Chem C*, 111, 3629–3635.

Knittel D and Schollmeyer E (2000). 'Permanent modification of fibrous materials with biopolymers', *Adv Chitin Sci*, 4, 143–147.

Korshak V V, Mozgova K K, Shkolina M A, Korostylev B N, Lipovetskaya O Y and Zasechkina A P (1962). 'Grafted copolymers. IX.', *Vysokomolekulyarnye Soedineniya*, 4, 1469–1473.

Kowalczyk T, Nowicka A, Elbaum D and Kowalewski T A (2008). 'Electrospinning of bovine serum albumin. Optimization and the use for production of biosensors', *Biomacromolecules*, 9, 2087–2090.

Kuroyanagi Y, Shiraishi A, Shirasaki Y, Nakakita N, Yasutomi Y, *et al.* (1994). 'Development of a new wound dressing with antimicrobial delivery capability', *Wound Repair Regen*, 2, 122–129.

Leuba S and Stossel P (1986). 'Chitosan and other polyamines: Antifungal activity and interaction with biological membranes', In *Chitin in Nature and Technology*, Muzzarelli R A A, Jeuniaux C and Gooday G W (eds.), Plenum Press, New York, p. 215.

Lewis H G P, Caulfield J A and Gleason K K (2001). 'Perfluorooctane sulfonyl fluoride as an initiator in hot-filament chemical vapor deposition of fluorocarbon thin films', *Langmuir*, 17, 7652–7655.

Leza M L, Casinos I and Guzman G M (1991). 'Graft copolymerization of 4-vinylpyridine onto cotton. The ceric ion concentration effect', *Angew Makromol Chem*, 184, 19–26.

Li D, Frey M W, Vynias D and Baeumner A J (2007). 'Availability of biotin incorporated in electrospun PLA fibers for streptavidin binding', *Polymer*, 48, 6340–6347.

Liesenfeld B, Toreki W, Moore D and Schultz G S (2007). Absorbent wound dressing with a non-leaching antimicrobial activity and a controlled-release bioactive agent. International patent application WO/2007/024972. 2007-March-01.

Lin J, Murthy S K, Olsen B D, Gleason K K and Klibanov A M (2003). 'Making thin polymeric materials, including fabrics, microbiocidal and also water-repellent', *Biotech Lett*, 25, 1661–1665.

Liu N, Sun G, Gaan S and Rupper P (2010). 'Controllable surface modifications of polyamide by photo-induced graft polymerization using immobilized photo-initiators', *J Appl Polym Sci*, 116, 3629–3637.

Liu S and Sun G (2006). 'Durable and regenerable biocidal polymers: Acyclic N-halamine cotton cellulose', *Ind Eng Chem Res*, 45, 6477–6482.

Liu S and Sun G (2008). 'Biocidal acyclic halamine polymers: Conversion of acrylamide-grafted-cotton to acyclic halamine', *J Appl Polym Sci*, 108, 3480–3486.

Liu S and Sun G (2009). 'New refreshable N-halamine polymeric biocides: N-chlorination of acyclic amide grafted cellulose', *Ind Eng Chem Res*, 48, 613–8.

Liu S, Zhao N and Rudenja S (2010). 'Surface interpenetrating networks of poly(ethylene terephthalate) and polyamides for effective biocidal property', *Macromol Chem Phys*, 21, 286–296.

Livage J, Coradin T and Roux C (2001). 'Encapsulation of biomolecules in silica gels', *J Phys: Condensed Matter*, 13, R673–R691.

Lu P and Hsieh Y L (2010). 'Layer-by-layer self-assembly of Cibacron Blue F3GA and lipase on ultra-fine cellulose fibrous membrane', *J Membr Sci*, 348, 21–27.

Luepke N P (1985). 'Hen's egg chorioallantoic membrane test for irritation potential', *Food Chem Toxicol*, 23, 287–291.

Luepke N P and Kemper F H (1985). 'The HET-CAM test: An alternative to the Draizer eye test', *Food Chem Toxicol*, 24, 495–496.

© Woodhead Publishing Limited, 2011

Luu Y K, Kim K, Hsiao B S, Chu B and Hadjiargyrou M (2003). 'Development of a nanostructured DNA delivery scaffold via electrospinning of PLGA and PLA–PEG block copolymers', *J Controlled Release*, 89, 341–353.

Ma M and Sun G (2005). 'Antimicrobial cationic dyes. Part 3: simultaneous dyeing and antimicrobial finishing of acrylic fabrics', *Dyes Pigm*, 66, 33–41.

Ma M, Mao Y, Gupta M, Gleason K and Rutledge G C (2005). 'Superhydrophobic fabrics produced by electrospinning and chemical vapor deposition', *Macromolecules*, 38, 9742–9748.

Martin T P, Kooi S E, Chang S H, Sedransk K L and Gleason K K (2006). 'Initiated chemical vapor deposition of antimicrobial polymer coatings', *Biomaterials*, 28, 909–915.

McDowall D J, Gupta B S and Stannett V (1982). 'The ceric ion method of grafting acrylic acid to cellulose', in Hon D N S, *Graft copolymerization of lignocellulose fibers*, ACS Symposium Series, Washington DC, pp. 45–55.

McDowall D J, Gupta B S and Stannett V T (1984). 'Grafting of vinyl monomers to cellulose by ceric ion initiation', *Prog Polym Sci*, 10, 1–50.

McQueen R H, Keelan Mand Kannayiram S (2010). 'Determination of antimicrobial efficacy for textile products against odor-causing bacteria', *AATCC Rev*, 10, 58–63.

Nevell T P and Zeronian S H (1985). *Cellulose Chemistry and its Applications*, Ellis Horwood Ltd., Chichester,

Park J Y, Kong B, Chi Y S, Kim Y and Choi I S (2009). 'Aryl Azide-based photografting of â-cyclodextrin onto cellulose diacetate fibers', *Bull Korean Chem Soc*, 30, 1851–1854.

Perelshtein I, Applerot G, Perkas N, Grinblat J, Hulla E, *et al*. (2010). 'Ultrasound radiation as a "throwing stones" technique for the production of antibacterial nanocomposite textiles', *Appl Mater Interface*, 2, 1999–2004.

Qian L and Sun G (2004). 'Durable and regenerable antimicrobial textiles: Improving efficacy and durability of biocidal functions', *J Appl Polym Sci*, 91, 2588–2593.

Rabea E I, Badawy M E, Stevens C V, Smagghe G and Steurbaut W (2003). 'Chitosan as antimicrobial agent: applications and mode of action', *Biomacromolecules*, 4, 1457–1465.

Ren X, Zhu C, Kou L, Worley S D, Kocer H B, *et al*. (2010). 'Acyclic N-halamine polymeric biocidal films', *J Bioact Compat Polym*, 25, 392–405.

Rudenja S, Zhao N and Liu S (2010). 'Surface interpenetrating networks of polyacrylamide in poly(ethylene terephthalate) as a means of surface modification', *Eur Polym J*, 46, 2078–2084.

Savard T, Beauliu C, Boucher I and Champagne C P (2002). 'Antimicrobial action of hydrolyzed chitosan against spoilage yeasts and lactic acid bacteria of fermented vegetables', *J Food Protect*, 65, 828–833.

Schmidt A, Buschmann H-J, Knittel D and Schollmeyer E 2003. Method for producing reactive cyclodextrins, textile material provided with same, and use of said cyclodextrin derivatives. U. S. Pat 7754877.

Schoukens G and Kiekens P (2009). 'New bioactive textile dressing materials from dibutyrylchitin', *Int J Clothing Sci Technol*, 21, 93–101.

Seong H, Kim J and Ko S (1999). 'Preparing chito-oligosaccharides as antimicrobial agents for cotton', *Textile Res J*, 69, 483–488.

Shin Y, Yoo D I and Min K (1999). 'Antimicrobial finishing of polypropylene nonwoven fabric by treatment with chitosan', *J Appl Polym Sci*, 74, 2911–2916.

© Woodhead Publishing Limited, 2011

Sibbald R G, Browne A C, Coutts P and Queen D (2001). 'Screening evaluation of an ionized nanocrystalline silver dressing in chronic wound care', *Ostomy Wound Manage*, 47, 38–43

Sohn S O, Lee S M, Kim Y M, Yeum J H, Choi J H and Ghim H D (2007). 'Aroma finishing of PET fabrics with PVAc nanoparticles containing Lavender Oil', *Fiber Polym*, 8, 163–167.

Son W K, Youk J H, Lee T S and Park W H (2004). 'Preparation of antimicrobial ultrafine cellulose acetate fibers with silver nanoparticles', *Macromol Rapid Commun*, 25, 1632–1637.

Srikar R, Yarin A L, Megaridis C M, Bazilevsky A V and Kelley E (2008). 'Desorption-limited mechanism of release from polymer nanofibers', *Langmuir*, 24, 965–974.

Sudarshan N R, Hoover D G and Knorr D (1992). 'Antibacterial action of chitosan', *Food Biotechnol*, 6, 257–272.

Sun X Y, Shankar R, Borner H G, Ghosh T K and Spontak R J (2007). 'Field-driven biofunctionalization of polymer fiber surfaces during electrospinning', *Adv Mater*, 19, 87–91.

Sun Y and Sun G (2001). 'Novel regenerable N-halamine polymeric biocides. I. Synthesis, characterization, and antibacterial activity of hydantoin-containing polymers', *J Appl Polym Sci*, 80, 2460–2467.

Tanner B D (2009). 'Antimicrobial Fabrics – issues and opportunities in the era of antibiotic resistance', *AATCC Rev*, 9, 30–33.

Thomas S and McCubbin P (2003). 'A comparison of the antimicrobial effects of four silver-containing dressings on three organisms', *J Wound Care*, 12, 101–107.

Tsuneda S, Saito K, Furusaki S and Sugo T (1995). 'High-throughput processing of proteins using a porous and tentacle anion-exchange membrane', *J Chromatogr A*, 689, 211–218.

Tungprapa S, Jangchud I and Supaphol P (2007). 'Release characteristics of four model drugs from drug-loaded electrospun cellulose acetate fiber mats', *Polymer*, 48, 5030–5041.

Vigneshwaran N, Kumar S, Kathe A A and Varadarajan P V (2006). 'Functional finishing of cotton fabrics using zinc oxide–soluble starch nanocomposites', *Nanotechnology*, 17, 5087–5095.

Wang D, Sun G and Chiou B (2007). 'A high-throughput, controllable, and environmentally benign fabrication process of thermoplastic nanofibers', *Macromol Mater Eng*, 292, 407–414.

Wang D, Sun G, Xiang B and Chiou B (2008). 'Controllable biotinylated poly(ethylene-co-glycidyl methacrylate) (PE-co-GMA) nanofibers to bind streptavidin–horseradish peroxidase (HRP) for potential biosensor applications', *Eur Polym J*, 44, 2032–2039.

Wang J and Cai Z (2008). 'Incorporation of the antibacterial agent, miconazole nitrate into a cellulosic fabric grafted with b-cyclodextrin', *Carbohydr Polym*, 72, 695–700.

Wang Y and Hsieh Y L (2008). 'Immobilization of lipase enzyme in polyvinyl alcohol (PVA) nanofibrous membranes', *J Membr Sci*, 309, 73–81.

Wendt C, Wiesenthal B, Dietz E and Ruden H (1998). 'Survival of vancomycin-resistant and vancomycin-susceptible enterococci on dry surfaces', *J Clin Microbiol*, 36, 3734–3736.

Wright J B, Lam K and Burrell R E (1998). 'Wound management in an era of increasing bacterial antibiotic resistance: A role for topical silver treatment', *Am J Infect Contr*, 26, 572–577.

© Woodhead Publishing Limited, 2011

Xing Q, Eadula S R and Lvov Y M (2007). 'Cellulose fiber-enzyme composites fabricated through layer-by-layer nanoassembly', *Biomacromolecules*, 8, 1987–1991.

Xu X L, Chen X, Ma P, Wang X and Jing X (2008). 'The release behavior of doxorubicin hydrochloride from medicated fibers prepared by emulsion-electrospinning', *Eur J Pharm Biopharm*, 70, 165–170.

Yamamoto K, Miwa Y, Tanaka H, Sakaguchi M and Shimada S (2002). 'Living radical graft polymerization of methyl methacrylate to polyethylene film with typical and reverse atom transfer radical polymerization', *J Polym Sci*, *Part A*, 40, 3350–3359.

Yan J and Chen J, (2003). Antimicrobial yarn having nanosilver particles and methods for manufacturing the same. U.S. Pat 6979491.

Yasuda K, Funabashi K and Chiyoda A, 1985, Antimicrobial fabrics having improved resistance to discoloration. U.S. Pat 4504541.

Zhang Y, Lim C T, Ramakrishna S and Huang Z (2005). 'Recent development of polymer nanofibers for biomedical and biotechnological applications', *J Mater Sci: Mater Med*, 16, 933–946.

Zhao N, Zhanel G G and Liu S (2011). 'Regenerability of antibacterial activity of interpenetrating polymeric N-halamine and poly(ethylene terephthalate)', *J Appl Polym Sci*, 120(1), 611–622.

© Woodhead Publishing Limited, 2011

16

Hospital laundries and their role in medical textiles

J. BERINGER and J. KURZ, Hohenstein Institutes, Germany

Abstract: Hospital laundries and medical textiles have always been closely linked because after each medical intervention the textiles involved have to be cleaned. This chapter deals with the historical aspects of cleaning and shows the development of hospital laundries using development in Germany as an example. The chapter discusses types of washers, the textiles used in hospitals, surfactants, bleaches and brighteners, and washing processes. The chapter also discusses testing and quality control in hospital laundries by reviewing the RAL quality marks used in Germany. However, the basic principles and general requirements can be applied to other industrialised countries.

Key words: hospital laundries, medical textiles, types of washers, surfactants, bleaches, brighteners, washing processes, quality marks.

16.1 Introduction

Hospital laundries and medical textiles or OR textiles, respectively, have always been closely linked. Even in the early stages of practical medicine after each medical intervention the textiles involved had to be cleaned. This chapter deals with the historical aspect and shows the development of hospital laundries and the corresponding environment from the past until today, using the example of development in Germany. The basic principles and general requirements can be applied to almost all modern industrial nations.

The technical development took place starting from the washtub via the first drum washers through to the state-of-the-art industrial high-tech processes with continuous batch washers, having nothing in common any longer with the traditional wash kitchen. Instead, today's hospital laundries are industrial production plants, tightly organised and calculated, wherefore hospital laundry or commercial laundry in general is more aptly referred to as industrial laundry.

The major key factors of the past and present development of hospital laundries may be summarised as follows:

- *Outsourcing*. External textile service companies replace hospital in-house laundries. Cost cutting in the healthcare system favoured the trend towards having the hospital laundry done by external services.
- *Quality assurance and hygienic safeguard* in particular. After having established effective measures for quality assurance and hygienic safeguard for the textile service companies as well as having received official

© Woodhead Publishing Limited, 2011

approval, it was possible and permitted to have the hospital laundry treated externally.

- *Interrupting the chain of infection*. The development of disinfecting laundering procedures represented an essential step towards reusing the hospital laundry in the framework of a return system.

16.2 Key issues of hospital laundries

16.2.1 Development of washing and drying machines, washing and centrifugal machines and washing extractors

In 1910 the German machine factory L.H. Lorch in Esslingen a. N. developed a vertical washing and drying machine ready for practical use, although it was not launched until 1913. Therefore, the year of 'birth' of the German washing extractor can be dated to 1913. However, washing extractors seem to have been practically unknown in Germany until the end of World War II, in 1945. Even Dr W. Kind, a well-known laundry expert, does not mention this kind of washing machine at all in his book published in 1949 which deals with commercial laundries. In the 1960s the situation changed and showed two distinguishable trends. The leading German machine factory, Gebr. Poensgen in Düsseldorf-Rath, adopted the principle of the washing spin-dryer, which the company Lorch introduced in 1913, while US machine manufacturers followed the principle of a high drum for domestic washers.

At the beginning of the twentieth century the success of American machines was repeated in the field of washing extractors. At that time technical progress came from the USA. German machine factories showed only cautious reactions at first. The Americans dominated the market, except for the German company Seibt & Kapp, Erdmannshausen, which discovered a niche in the field of smaller machines. But the Germans caught up quickly. In the mid-1960s they offered washing extractors of all sizes, whose capacity ranged from 10 to 150 kg.

Development of counter-flow washers, automated inline washers and continuous batch washers

The starting point for developing new washing processes was to become aware of the fact that the liquor which drained from the washing machine could be used very well for soaking the linen. Practical experience had shown that the heat of the liquor as well as the remaining soap still had a washing effect. It was quite difficult, however, to collect the liquor and then to empty it into the tub again. This complicated procedure was not in line with modern steam laundries aiming at achieving rational workflows.

© Woodhead Publishing Limited, 2011

Washing in counter-flow

The engineer Sulzmann concentrated on utilising remaining heat and detergent for a further washing process. He designed a washing facility with 12 washing machines connected to each other. The washing liquor could flow from one machine to the other. The water which flowed into the system was used for rinsing first, then for bleaching, washing and finally for pre-washing. Thus the principle of washing in counter-flow had been contrived and achieved sustained success. Only one third of the previous amount of heat and water and half the amount of detergent were needed. Furthermore, the new system reduced the work. A single person was able to handle a washing facility consisting of 12 machines.

Sulzmann sold the patent to the machine factory Engelhardt und Förster (E & F) in Bremen, who produced the first counter-flow facilities according to Sulzmann's system. The machines were loaded and unloaded in rotation so that the launderers permanently had to walk around the machine. The individual machines were manually taken from the counter-flow and then integrated back into the system.

For the technology of washing machines the principle of washing in counter-flow is the most important invention of the twentieth century. To date this principle is economically and ecologically second to none.

Continuous batch washers in counter-flow with individual machines

When the machine factory Gebr. Poensgen designed their counter-flow facilities they even went a step further arranging the individual washing machines as a carousel to allow loading and unloading always at the same position. Now the machines moved instead of the launderer in the system of E & F. The prominent aspect, however, was not the launderer, but to facilitate the loading of the spin-dryer which could be carried out in an easier and cost-saving way, when the laundry was always taken from the washing facilities at the same place.

Continuous flow washers or automated inline washers

When the counter-flow principle had fully matured at the end of 1950, machine manufacturers tried to improve the laundry process by automating the transport of the laundry and thus developed so-called automated inline washers. One of them was the washing conveyor belt WBS of the company Poensgen. It had a slanted washing pipe but could not gain market acceptance due to unsatisfactory washing results and insufficient batch separation. Nevertheless, the company Poensgen has to be given credit for being the first machine factory to implement the washing in continuous flow.

In 1961 the company Engelhardt & Förster, with the automated inline washer R 100, introduced a new principle for commercial laundry technology. Instead of the drums commonly used until then, E & F employed several aligned half shells similar to half external drums, in which the washing mechanics was generated by

© Woodhead Publishing Limited, 2011

means of special laundry movers, as well as the transport from one half shell into the other. According to literature E & F succeeded in reducing the consumption compared to initial counter-flow facilities even further, but did not manage to increase performance to the degree that the higher price of the facilities would have been amortised in the short term. Nevertheless Engelhardt & Förster's inline washing facilities captured a considerable market share. Hospital laundries, in particular, showed lively interest because the machine allowed them to divide the unclean side of the laundry from the clean one without major problems.

In the 1960s the machine factory Senking developed the transit washer. In principle it was a single-drum automated inline washer and came quite close to the later continuous batch washers. The transport of the laundry was carried out with spiral formed lifting rings.

The continuously working washing machines produced by the leading German laundry machine factories (Poensgen, Engelhardt & Förster, Senking) were followed by the single-drum and double-drum washers representing the second development phase. To date only two constructions of *single-drum continuous batch washers* have been developed, which consist of one drum. It is the Archimedia of the machine factory Voss and the continuous facilities ST 35 of the machine factory Ad. Schulthess.

In 1963 the company Pfaff in Neu-Isenburg near Frankfurt developed the conceptual design of the Archimedia, but only in 1970 the machine factory Voss in Sarstedt implemented it. The remarkable point about the continuous batch washer was the way of transporting the laundry from cycle to cycle. For this purpose in the interior an Archimedes' screw was tightly welded with the drum, which on the one hand formed the room for the individual compartments and on the other hand during one full rotation transported the batch to the next zone of the continuous batch washer. The compartments were provided with water, detergent and steam via a centric hollow axle in the screw. The complete drum was arranged self-supporting on positioning rolls at both ends. During the wash cycle the drum was swayed with a rotation angle of about 300 degrees. Eleven ribs were fixed to the drum and induced a steady rolling motion of the laundry. For transport of the laundry the drum was turned by 360 degrees after completion of the cycle. In this process the laundry stayed at the bottom and was not lifted up as in the other systems. The facilities worked with a divided counter-flow system with separated liquors of the pre-wash section, main wash section and final rinse section. After the company Vossin Sarstedt had stopped producing the Archimedia in 1979, first the Passat Group and, later, the company Kannegiesser continued to manufacture the facilities until 1995.

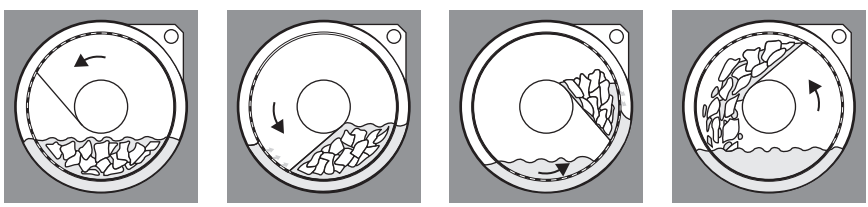
In 1975 the Swiss machine company Ad. Schulthess & Co. AG launched a counter-flow washing facility on to the German market. The ST 35 was a single-drum washer equipped with special inlet sluices for supplying water and detergent/bleaching agent to the individual sections. A similar system of outlet sluices discharged the dirty liquor. The soaking section worked with continuous flow. The

© Woodhead Publishing Limited, 2011

following sections were run with separated counter-flow. During the process of washing the rotation angle amounted to 300 degrees. The transport was carried out with a rotation of 360 degrees induced by spiral side walls at the bottom of the drum.

At about the same time in 1970 when the cycle washing facilities Archimedia was launched the machine factory Poensgen introduced the *double-drum continuous batch washers* PWZ to the market. From the outset it was designed for expansion. Optional further compartments could be added. While the drum was rotating, the slide sheet (see Fig. 16.1) pressed the laundry through the liquor and lifted it with part of the free liquor. This part of the liquor flowed through the holes in the interior drum back into the exterior drum. When the laundry during the cycle passed the upper half of the drum, it fell back into the liquor collected again. After completion of the cycle, transport was effected with a rotation of 360 degrees, now carried out in the opposite direction. The slide sheet took the laundry and transported it through the interior pipe into the next compartment. Every compartment was loaded and unloaded separately having the advantage of lower start-up current peaks, but the disadvantage of needing time and a complex control technology. Compressed air at a pressure of 2 bars entered the interior pipe in order to avoid a blockage. The PWZ was available in different sizes between 4 and 16 units for laundry batches of 35 kg. The hourly performance ranged between 300 and 1680 kg.

The continuous batch washer P 14 of 1970 produced by Senking in Hildesheim in principle could be called a double-drum construction, but also showed features of a one-drum construction. The interior drum was formed of individual drum units welded together. The unperforated separating walls of the compartments in the middle had an opening for transport. The interior drum shell was punched. The lifting sheets located in each compartment swayed the laundry and transported it to the following compartment. The interior drum made a rotatory motion of 360 degrees in one direction. Moving in reverse the laundry batch was transported with lifting sheets to the next compartment. The batch weight of the P 14 amounted to about 15 kg. Special types could manage batches up to 36 kg. The P16 was planned as a single-drum washer, but for reasons of laundry technology was enlarged to a double drum at certain locations. In contrast to line P14 the P16



16.1 Schematic illustration of the laundry moving in the interior drums of Poensgen's PWZ.

© Woodhead Publishing Limited, 2011

machines worked with a laundry transfer from the top. Around 1980 with the line P18 a single-drum/double-drum washer according to the Archimedes' screw but without an interior pipe was launched. In 1995 with the line 'Universal' Senking abandoned the continuous counter-flow principle and used the technology of changing baths which, in principle, conforms with a cycle counter-flow. The latest development is a bath changing machine without tanks.

The counter-flow washing facilities of Engelhard & Förster were also a double drum system with individual units, but had been considerably improved in various details. Every unit had its own drive, which was fixed above the closed exterior drums. During the wash cycle, in three seconds the interior drum slewed with a rotation angle of 180 degrees to the vertical reference line. After expiration of adjustable cycle time all interior drums rotated simultaneously by 360 degrees and thus transported the laundry. In this process transport spirals synchronously collected the laundry batches and transported them to the next unit.

About 1978 the continuous batch washers of the company Milnor Corporation was a further development being a double drum washer according to the system Arista Contrain. The interior drum had a rotation angle of about 240 degrees. With a full turn the laundry was transported to the next compartment. The automated inline washer has been continuously developed further. Today it is sold under the designations 76028 G3, 76039 G3 und 92048 G4.

In 1988 the Passat Group developed a small edition of Poensgen-Sulzmann's PWZ Module. Under the designation Ultra Tandem the smallest machine consisted of three drums divided into six segments with a load capacity of 15 kg each.

The double drum continuous batch washer Contrain 3500 of the company Dreher GmbH of 1977 treated the laundry with a rotating motion of about 220 degrees. With a full turn the laundry was transported to the next compartment. The French machine manufacturer Arista provided the basic design of the facilities.

The automated inline washer Continue of the Transferon Group is a double drum construction according to the principle of counter-flow. The company Kannegiesser merged the original Archimedia of Voss and the PWZ Module of Poensgen-Sulzmann and designed PowerTrans with an optimised water consumption and energy utilisation. The development of continuous batch washers is still under way, but the spectacular progress has decreased. All in all, however, this technology will continue being a most interesting future prospect.

16.2.2 Disinfection of the laundry

Public awareness for general laundry hygiene did not develop until 1961 when the German Law for Prevention and Control of Human Communicable Diseases, abbreviated as Federal Law of Epidemic Control (Bundesseuchengesetz), and in 1976 the Directive for Detection, Prevention and Control of Hospital Infections (Directive of the German Health Authority BGA) were enacted. In 1979 the

© Woodhead Publishing Limited, 2011

annexe to the Directive of the German Health Authority BGA Hygiene Requirements for Hospital's Washing, Hospital's Laundry Facilities and Washing Process and Conditions of Giving Away Hospital's Washing to Commercial Laundries was published and the Professional Association of the Administration Managers of German Hospitals (Fachvereinigung der Verwaltungsleiter deutscher Krankenanstalten e.V.) issued the Directives of Treatment of Hospital's washing in Hospital's in-house laundry facilities, Central Laundries and Commercial Laundries. Herewith the necessary measures to treat the hospital's washing were clarified. Additionally the List of Disinfections Tested and Approved by the German Health Authority (BGA-Liste) and the accident prevention regulation 'Laundry' (VBG 7y) defining the treatment of hospital's laundry from the laundry personnel's point of view were taken into consideration.

The new regulations issued by the health authorities induced a fundamental structural change of a hospital's laundry facilities because hospitals had to raise considerable finance to meet the new hygiene requirements. Therefore many hospitals considered having their laundry done externally, the more so as the official regulations envisaged such a measure. Thus at the beginning of the 1980s hospitals started to give their washing to external commercial laundries. In order to support an appropriate hygienic treatment of the hospitals' washing, in 1986 the German Institute for Quality Assurance and Certification (Deutsches Institut für Gütesicherung und Kennzeichnung) issued RAL a new quality mark for hospital laundry RAL-GZ 992/2 (see also Section 16.4), which specified the hygiene requirements of the German Health Authority and adopted it exactly to laundry issues.

The infectiousness of the laundry was divided into three categories: highly infectious, infectious and potentially infectious. Before leaving, highly infectious laundry has to be disinfected directly at the ward. Infectious laundry has to be collected in a particularly marked container (a laundry bag, for example). During the washing process the liquor must not be emptied until the laundry and the liquor have been disinfected. The washing procedures for potentially infectious laundry, however, only have to disinfect the washing itself, not the liquor.

Washing methods to be considered are thermal and chemo-thermal procedures. The thermal methods have to last 10 minutes at a temperature of 90°C or 15 minutes at 85°C. For each chemo-thermal procedure the German Health Authority issues lists of approved products and processes determining the conditions of application. The lists are binding only for infectious laundry.

The structural measures stipulate separating the clean and the unclean area. The passage for personnel has to be safeguarded with a sluice (airlock) as well as the transport of containers. It has to be possible to load the washing machines on the clean side and to empty them on the unclean side. All washing machines on the market are suitable as long as they meet specific requirements (see Section 16.2.1, which deals with washing machines).

With regard to personnel, conditions are stipulated under which work has to be done in the unclean area and which precautions have to be taken to protect

© Woodhead Publishing Limited, 2011

workers' health. A hygiene plan is demanded for all relevant activities in the laundry facilities in order to establish optimal hygienic conditions for all organisational processes. When clean laundry is transported, precise rules are to be followed for disinfecting the transport vehicles and the packing of the washed laundry. The quality control system according to RAL-GZ 992/2 for hospital laundry prescribes regular self monitoring and external controls.

16.2.3 Textiles for hospitals

Standards and guidelines

In 1964 the Professional Association of the Administration Managers of German Hospitals (Fachvereinigung der Verwaltungsleiter deutscher Krankenanstalten e.V.) founded the Expert Committee for Laundry Facilities (Fachausschuss Wäscherei). In 1965 practical work started with a statistical investigation of laundry facilities. This was a comparative compilation of costs for having the washing done in the hospitals' in-house laundries and in central laundries compared to market prices charged by commercial laundries. Until the middle of 1990 this investigation was considered an important source of information for administration managers and laundry owners.

This investigation showed that the hospitals were equipped quite differently with textile materials because former DIN standards were an inappropriate basis for the hospital's procurement of linen and clothing. The Expert Committee therefore decided to formulate its own procurement guidelines and assigned the task to the Hohenstein Institutes to generate technical specifications. In 1969 the Specifications for the Call for Tenders of Hospital Textiles (Unterlagen für die Ausschreibung von Krankenhaustextilien) were published. In the common use of language these technical specifications were abbreviated as Hohenstein Technical Specs (Hohensteiner TB's). Later the requirements for protective clothing made of blended fabrics were added and a book of 160 pages was issued containing all technical specifications and the major legal and normative regulations for the textile procurement of hospitals and for the laundry of the textiles.

After having published the technical specifications in 1969 they were circulated to such an extent that the German Institute for Standardisation DIN withdrew without substitution its standard 61 621 Fabrics for Hospital Bed Linen, Hospital Underwear and Clothing (DIN 61 621 'Gewebe für Krankenhausbettwäsche, – Leibwäsche und -bekleidung) in favour of the Technical Specifications for Hospital Textiles. In the 1990s however the European Standardisation became more and more important and the German Institute of Standardisation took up the topic again accepting responsibility for setting up a German work group in the framework of CEN TC 248 'Textiles and textile products'. Under the name 'Textiles in the healthcare system' the requirements for the major textiles in the

© Woodhead Publishing Limited, 2011

healthcare system have been stipulated. After the final discussions in 2001 a European prestandard was issued with a limited validity of two years in order to test the practicability of the contents. After the expiration of the 'probation period' the validity was extended again. In Germany the prestandard did not achieve the same level of awareness as the coexisting Technical Specs.

Interestingly sufficient administration managers were equally interested in the procurement of textiles and in the laundry facilities, because in 1982 the initial Expert Committee for Laundry Facilities was renamed as Expert Commission for Questions of Laundry Facilities and Textile Provision (Fachkommission für Wäschereifragen und textile Versorgung).

Textiles used for surgical procedures

Speaking of surgery textiles the first thoughts are scrubs for the OR personnel and surgical drapes for the patients. Then one imagines surgeons dressed in green or blue standing around an OR table together with their assistants close to electronic indicating devices illuminated with a big lamp. OR mask, surgical gloves and caps also belong to this scenario. This, however, has been a long technical and social development process.

The first pictures of surgeons protecting their street clothes date back to the 1890s. When in former times the surgeons' streetwear was blood-stained, this circumstance did not have negative connotations. It was very honourable to run around in town dressed with a blood-stained suit.

The new 'white era' for OR garments was ushered around the turn of the twentieth century. Gloves, masks and caps remained yet unknown. Still the turn of the twentieth century was a milestone for the use of textiles in the OR room, because streetwear was replaced with protective clothing. The step towards using surgical face masks was not taken until about 1930. Only from then on are pictures to be found with surgeons and assistants wearing masks. The masks were probably made of simple cotton cloth.

After World War II the provision of textiles to surgeons and patients improved rapidly. To start with the general use of protective gowns for the surgeons and surgical drapes for the patients was introduced. The OR textiles were exclusively made of cotton. First, the garments were protected with a rubber apron, later with a plastic-coated textile apron particularly during operations with larger amounts of liquids involved.

In the 1960s the progressively oriented hospitals gave their OR garments a water repellent finish to protect the surgeon from contact with blood and other bodily liquids. Thereby it quickly became apparent that, due to their porosity, cotton textiles were only suitable to a limited extent to repel liquids effectively. The next consequent step was to use fabrics with an inherent density as high as possible like the blended fabrics created in those times made of 50% polyester and 50% cotton which were very appropriate.

© Woodhead Publishing Limited, 2011

The water repellent finish of textiles started development in the field of OR materials. Now the textile manufacturers tried to use the 'waterproof textiles' already tried and trusted in the private sector also for the OR applications. Although it seemed to be easy at first, considerable start-up problems occurred because the OR textiles not only had to be washable but also sterilisable as often as possible. In general one talked about at least 50 cycles but the desired target was 100 cycles.

In the 1970s there were only two products in Germany which had adequate breathability and absolute watertightness at the same time. These products were SympaTex® and GORE-TEX®, the first one being cheaper but not applicable for OR textiles as it was not sufficiently resistant to sterilisation, leaving only GORE-TEX®. With the use of these textile laminates a new hygienic quality for protective gowns and drapes for patients became possible. Now the OR textiles were watertight and breathable at the same time.

After the law for medical products had been implemented not only the products themselves were improved but also the washing processes changed. For recycling medical products quite a number of important parameters have to be observed which are described in detail in the literature and in the standards.

16.3 Impact of hospital laundries on the hygiene of medical textiles

16.3.1 Surfactants

As a result of hydrogenation facilities for coal liquefaction being developed for high pressures the synthesis of fatty alcohols from fats succeeded in the 1930s. Instead of fatty acids being used for producing soap, fatty alcohols now formed the basis of the process. Instead of neutralising the fatty acid with alkalis the fatty alcohol was converted with sulfuric acid. So the fatty alcohol sulfate was received which, being a sodium salt, possessed the same foaming ability as soap. Additionally, it showed outstanding washing power, being neutral and resistant against the substances that cause water hardness. Thus a new mild detergent was born. It was launched under the name FEWA in 1932.

The development of the new detergent became feasible because the chemical industry was able to provide enough fatty alcohols. Nature acted as the chief source of supply. Chemists discovered that spermaceti and liquid sperm oil of marine mammals are pure fatty alcohol and fatty acid esters. By simply splitting the esters one received fatty alcohols and fatty acids being starting products for detergents.

With the beginning of World War II in 1939, whale hunting in the polar sea came to a sudden end. Thus supplies of biological fat were no longer available. One had to come to terms with using paraffin, the coal-to-liquid waste produced

© Woodhead Publishing Limited, 2011

during the extraction of brown coal. But petroleum also contains large amounts of paraffin hydrocarbons.

The actual problem lay in the task of inserting a group into the paraffin which was accessible for a chemical transformation. And indeed it was possible to produce a paraffin fatty acid by means of a catalysed oxidation. After neutralising it with alkali, soap was obtained. The paraffin fatty acids could also be reduced to paraffin alcohol, generating hard water resistant alkyl sulfates of the same quality as the fatty alcohol sulfates FEWA was made of.

The paraffin oxidation led to further important raw materials for detergents. Combined with benzene, a new raw material named alkylbenzenesulfonate was developed, representing one of the main components of heavy-duty laundry detergents and light-duty detergents (Fig. 16.2) for delicate textiles. The initial difficult biogradability could be improved by a change to unbranched paraffin chains (Fig. 16.3).

With the conversion of fatty alcohols with polyglycol ethers new washing active substances with particular emulsification and dispersion properties were produced. They can not dissociate in aqueous solutions and therefore are named non-ionic surfactants, being applied for almost every aspect of cleaning technology. By virtue of a better detergency at low temperatures the trend for these washing raw materials, referred to as fatty acids polyglycol ethers, leads towards a lower degree of ethoxylation.

Washing raw materials made of renewable resources represent the state-of-the-art developments in the surfactant research. They are generally referred to as sugar surfactants being alkyl polyglucosides (APG) and fatty acid glucamids (GA).

Despite all new developments concerning surfactants during the last decades, alkylbenzenesulfonates are the mostly applied washing raw materials.

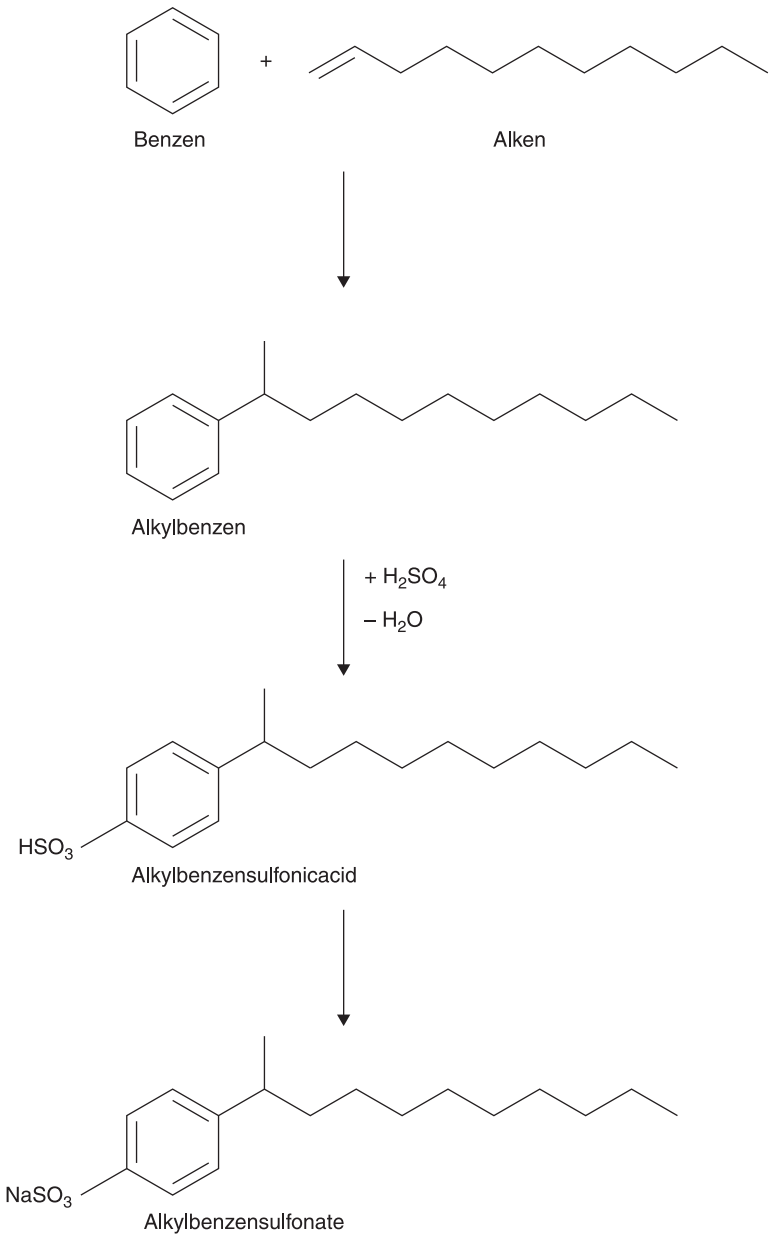
16.3.2 Bleaching and optical brightening of the laundry

Chlorine bleach

Chlorine bleach liquor and chlorinated lime were the two most important bleaching agents in the early stages of commercial laundries. In 1785 the French chemist C.L. Bertholet (1748–1822) produced the first chlorine bleach liquor through passing chlorine gas into a potassium carbonate solution with potassium hypochlorite as a result. As this happened in Javelle, a suburb of Paris, the chlorine bleach liquor was named Eau de Javelle. The name remained unchanged until the beginning of the twentieth century, although the potassium hypochlorite had been replaced by sodium hypochlorite.

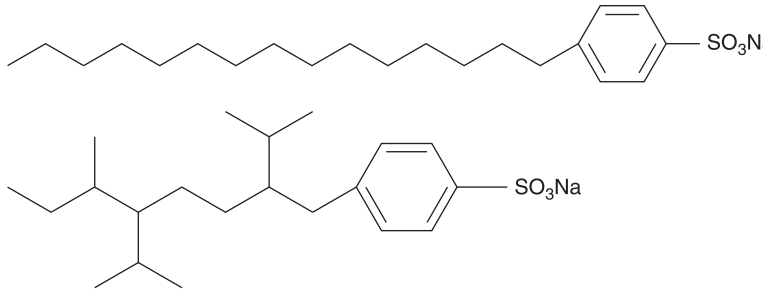
In contrast to the fluid chlorine bleach liquor the chlorinated lime represents the most convenient form in which chlorine can be traded. It is an uncoloured crumbly powder and also keeps its chlorine content during extended periods of storage at a dry place. For this reason the chlorinated lime produced in an industrial process

© Woodhead Publishing Limited, 2011



16.2 Synthesis of alkylbenzenesulfonate.

© Woodhead Publishing Limited, 2011



16.3 Linear alkylbenzenesulfonate (top) and highly branched alkylbenzenesulfonate (below).

for the first time in 1799 by the British chemist Smithson Tennant (1761–1815), was the more popular bleaching agent among the commercial laundries. The chlorine content averaged between 25 and 36%.

Some days before applying the chlorinated lime it had to be steeped in cold water in a ratio of 1:10 to 1:20 depending on the chlorine content of the lime. Then the supernatant alkaline water was the bleaching solution.

The laundry was treated with the cold 5–6% bleaching solution for about 15 minutes. Afterwards the laundry had to be rinsed until the smell of chlorine disappeared. Sodium bisulfite as antichlor was added to the last rinsing bath.

Hydrogen peroxide and addition compounds

When, in 1907, Persil with bleaching perborate was launched, commercial launderers also paid attention to household products and had to learn that these, with regard to bleaching, cleaned the laundry more gently.

The German company Henkel & Cie. from Düsseldorf introduced Oxygenol, the first bleaching agent with oxygen, to the market. It could be added to the so-far-used alkaline soap suds in the laundries. One did not have to steep an additional bleaching bath with subsequent antichlor treatment, but only had to add the new product to the hottest bath.

Safer working and facilitated processes were the keys to success of the bleaching agents with oxygen. During the following years the bleaching agents with oxygen put chlorine bleachers out of the market, although never completely, however, as chlorine, correctly used, also has undeniable advantages. This situation has remained unchanged until today.

In the early days commercial laundries seldom used hydrogen peroxide as a commercial liquid, as it was not sufficiently stabilised and therefore decomposed quickly. They preferred to produce hydrogen peroxide themselves by transforming sodium superoxide with acid. Sodium perborate, however, was used by laundries

© Woodhead Publishing Limited, 2011

in the original powder form, although it did not dissolve well in cold water. Through the decades the application of bleaching agents with oxygen became an accepted standard for commercial laundries.

Peracetic acid

Although the application of bleachers with oxygen was very convenient for everyday practice in laundries, they failed for washing temperatures around 60°C and below. During the 1960s this necessity resulted from the increasing introduction of mixed fabrics of polyester and cotton to the market. This type of laundry was washed with lower temperatures and was treated with peracetic acid as bleaching agent.

Through the years the washing processes with peracetic acid were also applied for coloured laundry and were accepted for disinfectant washing procedures of hospital laundry. Peracetic acid is dosed in liquid form and well stabilised concerning the production. Apart from hydrogen peroxide, peracetic acid is the bleaching agent that commercial laundries most frequently apply.

Optical brighteners

After World War II the chemists of the German company Farbenfabriken Bayer in Leverkusen found a replacement for the washing blue being used as the optical brightener. In contrast to blueing, where the yellowness of the laundry is compensated to a light grey, perceived as being 'whiter' by the human eye, optical brighteners really increase the whiteness of the laundry. They absorb light in the ultraviolet and violet region of the electromagnetic spectrum and re-emit light in the blue region, thus also compensating the yellowness, but additionally increasing the sensation of whiteness.

Since 1941 mainly optical brighteners based on heterocyclic substituted stilbene have been applied. These products can be used to brighten up cotton, viscose and polyamide. For polyester fibres substituted divinylstilbene is suitable.

Optical brighteners gave the whiteness of laundry a new significance. Now it was not sufficient that the laundry was clean. It also had to 'shine', thus radiating light in the strict sense of the word. Comparing today's white to the whiteness of 50 years ago achieved without optical brighteners, the laundry at that time really looked yellowish.

16.3.3 Washing processes

Basic findings during the initial years

The steam laundries founded towards the end of the nineteenth century basically adopted the washing processes of the former washerwomen, replacing the manual

© Woodhead Publishing Limited, 2011

labour with machines. They heated the washing liquor with saturated steam. Chemical substances were used instead of photocatalytic bleaching (putting the laundry outside on the lawn).

At that time the interaction of the individual components of the washing processes required to achieve an optimised washing result was unknown. This was hardly surprising and it was some time before the four determining components of a washing procedure – mechanics, chemistry, temperature and time – were combined. It was only in the 1930s that Dr Herbert Sinner investigated the influence of these components on the washing process, interpreted the results and applied the findings in practice (see Section 16.9.8).

From 1900 to 1915 the washing procedures underwent a remarkable change. While around the turn of the century the laundry, after having been treated in the washing machine, was first examined concerning remaining dirt and stains; 15 years later, this job was entirely abandoned. Right from the beginning, particularly dirty laundry was put into the steam tub for 20–30 minutes at boiling temperature. Soap and soda remained as laundry detergents, being joined by washing soda (sodium silicate and soda) for soaking. For superior washing results two machine hot wash cycles were carried out. The second wash bath served as the first bath during the next wash cycle.

Bleaching with perborate or hydrogen peroxide was combined with the wash cycle at high temperatures already known from the household brand detergent Persil. Obviously, no satisfying solution for stabilising the liquid hydrogen peroxide was yet found and the bleaching agent decomposed during storage. But with a peroxide generator the launderers were able to produce the peroxide solution directly before the bleaching process.

For the chlorine bleaching process, chlorine bleach liquor replaced chlorine lime and was freshly made with special devices directly in the laundry. Round about 1925 steam laundries changed their washing philosophy again. The soaking periods became shorter, being about two to three hours, which improved the laundry's workflow. For the application of soap, soda and perborate or hydrogen peroxide the system with two baths became established. For the use of detergents with solvents, the procedure with a single bath remained. Chlorine bleaching was carried out after the second wash bath before rinsing.

The treatment of hot wash laundry did not change. Still boiling the laundry was the most important step for cleaning the textiles (see Section 16.9.2). In 1921 Otto Neumann, who was an engineer of Berlin's municipality, said that the boiling process should add up to at least 45 minutes and all washing machines had to be equipped with a safety steam tube, a so-called foam tube, preventing overpressure in the washing machine.

It was perfectly obvious that under such tough conditions the laundry would be damaged. In addition to that there was a high concentration of soda and carbonic and silicic salts having their origin in the hardness minerals of the water. In consequence the laundry was hard and rough. In particular, linen fuzzed considerably.

© Woodhead Publishing Limited, 2011

From 1925 to 1950

In the literature of around 1925 a certain lack of security with respect to the appropriate washing procedures is to be found. Even in books with a high technical standard no clear definition of procedural requirements for washing processes was given. Instead the authors confined themselves to list the well-known washing procedures applied in practice, which were mainly developed by laundry detergent producers. This changed by 1935, however, when the washing processes, which had been systematically developed in the USA, were made known in Germany and put into practice by the economic base of the German Laundry Association (Wirtschaftsstelle des Deutschen Wäschereiverbandes) in accordance with the specific national framework. Now, the chemical and physicochemical laundry processes had been scientifically analysed and the correct conclusions drawn.

The procedure described was generated by the office for research and economy of the Reich's professional association (Reichsinnungsverband). It complied in the main with the American recommendations for a process with several wash suds. In Germany it was called 'Soda–Soap Procedure'. When instead of chlorine bleaching liquor the 'modern' oxygen bleaching was used, the washing procedure was shortened considerably, because the sodium perborate and the hydrogen peroxide could be added to the third soap bath. Furthermore the chlorine bleaching bath along with the antichlor was no longer required. For particularly dirty laundry the soaking before washing was recommended, as well as enzymatic products against strong stains of protein.

Until the end of World War II in 1945, in Germany the principles for laundry procedures, still valid today, have been developed. The first wash bath lasted 10–15 minutes at a temperature of 30–40°C with addition of washing alkalis. For extremely dirty laundry a second wash bath followed. Then the main wash bath with addition of peroxide at a temperature of 80°C succeeded for about 15 mintues. Subsequently the laundry was rinsed four times with warm water, then once with cold water. The chlorine bleaching solution was used in the fifth rinse bath. Afterwards the laundry had to be treated with antichlor in a further bath.

In summary, it can be said that between 1925 and 1950 there are to be found six major changes in the development of laundry detergents and washing procedures. First, the fact had been realised that a high alkalinity and a high temperature for a long period of time, more than 30 minutes, for example, would lead to severe fibre damage. Therefore soda was only used for the pre-wash at low temperatures.

Second, under immediate addition of soap to the washing liquor with hard water, lime soap developed being inactive for washing. It could only be reformed to wash-active sodium bicarbonate soap by cooking. Therefore the combination of soap–sodium carbonate was changed to sodium carbonate–soap. This was substantial progress for improving the washing procedures.

Third, the washing soda, at first preferred by all laundry detergent producers, was partially replaced or supplemented with products containing sodium silicate.

© Woodhead Publishing Limited, 2011

One realised that washing alkalis containing sodium silicate did not only possess an outstanding cleaning effect, but also contributed to treating the laundry gently. Nowadays, the prohibition to apply products containing sodium silicate in governmental laundries imposed in the 1930s appears odd. Even commercial laundries which worked for local communities or public authorities had to adhere to this prohibition.

Fourth, the chlorine bleach with 0.5–1 g of active chlorine per litre at a temperature of around 60°C was replaced by the oxygen bleaching with hydrogen peroxide, perborates and percarbonates, respectively. This change was accompanied by long scientific discussions and an initial refusal in the laundry sector. It started, when finally it became clear that the oxygen bleaching would not be more expensive than the existing chlorine bleach. Apart from the chemical aspect there also was a psychological advantage in favour of the oxygen bleach. Now, customers could be led through the laundry facilities without being exposed to the smell of chlorine which was linked with the destruction of the washing.

Fifth, when from 1933 onwards blended fabrics made of rayon staple with cotton were increasingly launched as well as rayon staple, laundry procedures had to be adapted to the new sensitivity of these new materials. More gentle procedures had to be developed, for which synthetic surfactants were very appropriate. Fatty alcohol sulfonates (Sekurit), fatty acid condensation products (Sunova), Mersolat and its derivatives (MS-Seife, Rif-Pulver) and non-ionogenic products (U119) were introtroduced.

From 1939 onwards, during the war years, synthetic surfactants dominated the laundry detergent market, as the fats, required for the production of soap, were needed for nutritional purposes. When the fatty acid, however, was available, it was made resistant to hard water by replacing the carboxyl group by a sulfate group. One succeeded in producing synthetic surfactants without any fatty acid by sulfurisation of paraffin and ethoxylation. Chemical advances guaranteed that laundries were provided with fairly sufficient amounts of detergents during World War II, in contrast to World War I, where rationing and regulations were imposed by the so-called war associations. After World War II detergent chemists could adopt the findings of the war years and continue to advance the further development of synthetic surfactants.

Sixth, during the 1920s the introduction of ion exchangers had already made the softening of water a state of the art, although smaller laundries still used soda for many years. With inorganic complexing agents, such as Calgon, and organic products, such as Trilon, products that were easy to use in commercial laundries were launched.

Overall, during the years from 1925 to 1950 laundry procedures took a giant step. In principle, the basics of laundering were known. With the help of the detergent producers and the office for economy and research of the Reich's professional association (Reichsinnungsverband) laundries had learnt to organise the courses of the procedures correctly. By establishing a quality label for

© Woodhead Publishing Limited, 2011

appropriate laundry care the option existed to control laundry procedures objectively and to optimise laundering quality as well as the gentle treatment of the laundry.

From 1950 to 1970

At first, laundry procedures did not change much. There was sufficient soap and soda again, but washing machines were the same as before or during the war as well as the laundry. The number of different types of detergents increased many times over during these 20 years. Quite a range of products was developed from the prior main components, soap and soda being adapted for their use during the laundry process. Now, there were heavy-duty detergents, sole detergents, main wash and pre-wash detergents as well as products for coarse or coloured materials. Pre-wash agents which contained specific alkalis, special surfactants, phosphates or bleachers could be used for treating particular soilings. The start of automatic dosing led to compromises concerning laundry procedures.

Since the 1950s quite a number of counter-flow facilities were used in German laundries, produced by the German companies Engelhardt & Förster and Gebr. Poensgen. Standard laundry procedures were defined for these facilities. As for the classic laundry procedures the most important components were the heavy-duty detergents or main wash detergents and the bleachers.

For disinfecting a hospital's laundry during washing, in addition to the familiar detergents a chlorine containing product, mostly Tryplosan made by Henkel, was used. Further examined disinfecting agents could be found on a list published by the German Health Authority.

In summary, it can be said therefore, that during the period from 1950 until 1970 commercial laundries had a variety of effective products at their disposal for washing dirty textiles. However, most of the products were named according to their purpose and no longer according to their contents. In a few cases the ingredients were known. But this did not matter a great deal. The main point was having clean laundry in the end. This was the final end of the era of 'soap and soda' or vice versa. Discussions in the literature about laundry procedures also virtually ceased.

From 1970 to the present

Since 1970 a major change has taken place, namely, that the automated inline washers have become a substantial part of laundry technology, starting with the continuous batch washer Archimedia made by the German machine factory Voss in Sarstedt. Thus the hitherto existing classic laundry procedures with separated baths were replaced with flow processes. They dealt with maximising stain removal as well as minimising the necessary amounts of detergents and agents. Experts for laundry procedures were needed to accommodate both aims. Laundry

© Woodhead Publishing Limited, 2011

owners and their launderers were often unable to cope with this situation themselves, so detergent producers with their technical field service force took on this task, and still do. The detergent producers keep the development of their detergents as a carefully guarded secret and the specialised press only refers to praising the efficiency, seldom or never to the ingredients themselves.

On the other hand the laundry procedures like those for blended fabrics of polyester and cotton are well recorded. They were developed with considerable effort during the 1970s in order to introduce a new kind of work clothing to a large market. Washing these materials was not a problem in itself. The difficulties resulted from the necessity to create laundry procedures in such a way that the subsequent tunnel finishing achieved a satisfactory smoothing effect.

A further important change concerning the laundry procedures was the adoption of peracetic acid as bleaching or disinfecting agent for hospital laundry respectively. This came along with a changeover from manual to mechanical dosing, which has been generally implemented for automated inline washers, being optional for washing extractors. Over the years, however, the dosing technique for products in powder form advanced to the point where it was superior to manual dosing. Detergent producers even tried to achieve mechanical dosing for their products right from the outset. After all, the development of a mechanical dosing technique was a logical consequence of commercial laundries becoming more technologically orientated.

16.4 Testing and quality control of hygienic properties in hospital laundries

16.4.1 The RAL quality mark 992

Historical development

During World War II it was impossible to establish a common standard for laundries. The underlying idea for appropriate laundry care was a gentle fibre treatment during the washing process, which the launderers therefore could only put into practice when their machine technology was brought up to date again and also the supplying industry could deliver innovative products of constant quality. This was accomplished in 1953 and the quality mark could be established.

The quality specifications underlying the application to the German RAL (National Board for Delivery Conditions) were published in the German technical magazine *Wäschereitechnik und Chemie* (*Laundering Technology and Chemistry*) allowing experts to discuss and complete it. The chief points, however, remained unchanged. After the quality mark had been registered as a quality brand at the German patent office, all discrepancies about the design of the logo and the market position of the quality mark were settled. Within a few years there were no different opinions about the topic ‘gentle treatment of the laundry’ any longer.

© Woodhead Publishing Limited, 2011

16.4 Logo RAL-quality mark 992 'Appropriate Laundry Care'.

The contents of the RAL specification were state of the art. Compared with today the quality mark of 1953 only referred to the actual laundry process. In 1970 further criteria were introduced. In 1971 the new articles of association as well as the new quality and test regulations were issued. The association was also renamed, now calling itself Gütegemeinschaft sachgemäße Wäschepflege e.V. (Quality Association for Appropriate Laundry Care). The quality mark itself was only changed concerning the signature. The logo itself remained as it was (Fig. 16.4).

It became obvious that hygiene would play an important role for the laundries, as they started to orientate themselves towards the healthcare system, thus being the beginning of a structural change in the laundry sector until the 1980s. The hospital in-house laundries treated nearly all the accruing laundry of the healthcare system until the 1970s. The guidelines for the hygienic cleaning of laundry by external launderers published by the German Health Authority at that time lead to a standardisation of the requirements. Thus the way was paved for giving the hospital laundry to commercial launderers. In cooperation with Professor Dr med. habil. Walter Steuer from the Medizinisches Landesuntersuchungsamt Stuttgart (Regional Analytical Authority for Medical Issues in Stuttgart) and with the Verband der Krankenhausdirektoren Deutschlands e.V. (Association of German Hospital's Directors e.V.) clear instructions were given regarding how to meet the requirements of the German Health Authority as well as how to comply with the limit values. To start with the Gütegemeinschaft (Quality Association) and the Verband der Krankenhausdirektoren Deutschlands e.V. (Association of German Hospital's Directors e.V.) issued two-page recommendations, until in 1986, the RAL-RG 992/2 Krankenhauswäsche (RAL quality mark for hospital laundry) embodied a new milestone in the history of the Quality Association.

© Woodhead Publishing Limited, 2011

The idea of a quality mark was transferred to other areas of cleaning laundry and in 1999 a new quality mark RAL- GZ 992/3 was issued dealing with laundering the washing of the food processing industry.

16.4.2 The RAL quality mark for commercial laundries

RAL 992/1 – Household linen and contract textiles

With this quality mark the laundries started their RAL quality assurance. At that time cleaning household linen was their main business.

RAL 992/2 – Hospital laundry

Initally each hospital had its own in-house laundry facilities. At the end of the 1970s the machines were past their prime and would have had to be replaced. On the other hand commercial laundries were technically equipped in an exemplary manner and had free capacities available. Therefore it seemed natural to give hospital laundry to the commercial sector. However, this could not be implemented without strictly respecting the hygienic aspect. The laundries had to establish a hygiene management for their facilities. This happened in close cooperation of those responsible in the hospital, with the Federal State Health Authority and the German Health Authority respectively as well as with the Hohenstein Institutes.

RAL 992/3 – Laundry of the food processing industry

The contact with food requires a high degree of hygiene. Textiles which come into contact with food also have to comply with a defined hygienic status. Until 1998 there was no binding guideline. In cooperation of those responsible in the food sector with the Robert Koch Institute, the laundries and the Hohenstein Institutes, quality and test regulations have been developed which meet the normally necessary hygienic standard for the food processing industry and can be implemented for commercial laundries. The quality mark also contains the provisions of the European standard DIN EN 14065 Laundry Processed Textiles – RABC (Risk Analysis and Biocontamination Control). Workwear for the hospital kitchen, for example, has to be treated according to such hygienic directives.

The quality mark abroad

Until 1990 the RAL quality mark for appropriate laundry care was a matter of importance only in Germany. In the course of the harmonisation of procedures in economic life across Europe, Austrian and Swiss laundries joined. In 2001 Slovenian launderers and during the last few years a Slovakian laundry has affiliated. It is expected that during the next few years launderers from Poland, Greece and the Czech Republic will apply for the quality mark.

© Woodhead Publishing Limited, 2011

Meanwhile in Japan the RAL quality mark is met by 13 laundries. After having weighed the pros and cons of the international quality systems, including the European RABC-System, the RAL quality mark was chosen, being the only system with well-defined standards for the technological requirements and hygiene limits.

Meanwhile a great, even worldwide, interest in the German RAL quality mark is shown, with China and the USA being only two examples.

16.4.3 European Standard EN 14065 RABC

In 1998 the European Committee for Standardisation CEN (Comité Européen de la Normalisation) in Brussels started to transfer the hygiene management system RABC system (Risk Analysis and Biocontamination Control System) adopted by the food processing industry, to the laundering process of textiles. On the initiative of the French national organisation for standardisation 'afnor' (association francaise de normalisation), an international workgroup of the Technical Committee 248 'Textiles and Textile Products' with their secretariat at the British Institute for Standardisation, BSI, dealt with settling the contents and harmonising it with established regulations. In February 2003 the standard with the number DIN EN 14065 was issued under the German title In Wäschereien aufbereitete Textilien – Kontrollsystem Biokontamination (Textiles – Laundry processed textiles – Biocontamination control system). The standard's fields of application extend to all areas where textiles are cleaned and afterwards should have a specific hygienic status. It is a standard to improve the process mastery, but does not imply concrete requirements in numbers for the final status of laundered textiles. Each user of the standard can define values appropriate for his laundry.

In compliance with the RABC system (Risk Analysis and Biocontamination Control System) a brochure for implementing the system in the operational quality management system was designed. The so-called intex certificate can be awarded for successful practical implementation.

16.5 State of the art in hospital laundries

All these developments mentioned above paved the way for high-tech hospital laundries with sophisticated logistics systems which nowadays are seldom hospital in-house facilities. Instead the larger part of the hospital's laundry is dealt with by textile service contractors offering a so-called full service.

The present state of the art of hospital laundries in Germany can be explained best along the production chain. The dirty laundry is collected with vans having a modular separable shipping space for clean and dirty laundry. When the washing is delivered to the unclean section of the laundry facilities, the potentially infectious laundry is distinguished from the infectious one. The latter is not allowed to be sorted, but has to be put together with the laundry bag directly into the automated

© Woodhead Publishing Limited, 2011

inline washer for the disinfecting process. The applied laundry procedures are predominantly economical chemothermic processes using an oxygen based disinfecting agent, peracetic acid. After the laundry has been dewatered, either in a centrifuge or a dewatering press, the final drying is carried out in a tumble dryer. This is followed by an inspection and patching of the laundry if necessary. Before the final sterilisation process the textile sets for the most common operations are made up and finally returned to the hospital in the above-mentioned van.

16.6 Future trends

The future direction of development that the hospital laundries will take can be described most aptly with two keywords: sustainability and profitability. Resources such as water and energy are presently integrated in a sophisticated cycle process which will be perfected further. The next task will be to find an effective way to withdraw process chemicals that have not been used during the cleaning procedure. In all probability, a further reduction of freshly added process water will not be possible, as the 'healthy' limit has already been undercut. Nowadays, record values of 3 litres of fresh water and less to clean 1 kg of laundry can not be reduced without declining good washing performance.

Therefore it is important for the future to place special emphasis on the sustainability of the processes in hospital laundries in connection with optimising the re-use of textiles and saving the available resources. The safety and quality of the laundry process, however, should by no account be affected. This is the only way to maintain the present hygienic status in the hospitals as well as the best medical care for the population.

16.7 Sources of further information and advice

Sources of further information on the subject of hospital laundries, medical textiles and processing textiles are listed in the following:

Robert-Koch-Institut (www.rki.de)
RAL-Gütezeichen (www.ral-guetezeichen.de)
RAL-Gütezeichen Sachgemäße Wäschepflege (www.waeschereien.de)
RABC (www.rabc-wfk.com/)
Hohenstein Institute (www.hohenstein.de)
wfk-Forschungsinstitut für Reinigungstechnologie e.V. (www.wfk.de)
intex Industrieverband Textil Service (www.intex-verband.de, www.intex-med.de)

16.8 Further reading

Andès L E (1922). Wasch-, Bleich-, Blau-, Stärke- und Glanzmittel, 2. verb. Wien/Leipzig, Auflage.
Arringten L J (1990). *From Small Beginnings*, Salt Lake City, UT.
Autorenkollektiv (1976). *100 Jahre Henkel 1876–1976*, Düsseldorf.

© Woodhead Publishing Limited, 2011

Autorenkollektiv (1986). *7.000 Jahre Handwerk und Technik*, Herrsching.
Autorenkollektiv (2003). Gütegemeinschaft sachgemäße Wäschepflege e.V.; Kultur und Geschichte der textilen Sauberkeit, Bönnigheim.
Autorenkollektiv (2003). Gütegemeinschaft sachgemäße Wäschepflege e.V.; Von der Dampfwaschanstalt zum Textildienstleister, Bönnigheim.
Barleben I (1951). Kleine Kulturgeschichte der Wäschepflege, Düsseldorf.
Bertrich F (1966). Kulturgeschichte des Waschens, Düsseldorf.
Bottler M (1908). Bleich- und Detachiermittel der Neuzeit, Wittenberg.
Bottler M (1924). Bleich-, Reinigungs-, Wasch-, Detachiermittel, Bleichverfahren und Bleichapparate der Neuzeit, Wittenberg.
Buchholz W (ca. 1870). Allgemeines Wäschebuch, Hamburg.
Cordes W (1932). Waschmaschinen, Lette.
Gawalek G (1962). Wasch- und Netzmittel, Berlin.
Grothe H (1884). Katechismus der Wäscherei, Leipzig.
Henkel & Cie. GmbH (Hg.) (1976). Waschmittelchemie – Aktuelle Themen aus Forschung und Entwicklung, Heidelberg.
Kurz J (1968). Betriebsabrechnung und Kalkulation in der Wäscherei, München.
Kurz J (2006). Kulturgeschichte der häuslichen Wäschepflege, Heidelberg.
Kurz J (2007). Die Kulturgeschichte der professionellen Textilpflege, Edition Braus – Wachter Verlag, Heidelberg. ISBN 978-3-89904-314-3.
Kurz J (2007). Die technische Evolution der Dampfwäscherei, Edition Braus – Wachter Verlag, Heidelberg. ISBN 978-3-89904-291-7.
Kurz J (2007). Französische Wäsche und deutsche Textilreinigung, Heidelberg.
Kurz J *et al*. (1973). Lexikon für Textilreiniger, München.
MEWA (1983). Die Geschichte einer Dienstleistung 1908–1983, Wiesbaden.
Radeck O (1912). Die Behandlung der Wäsche nach den neuen Erfahrungen, 10. Auflage, Freiburg (Schlesien).
Reumuth H (1965). Der Schmutz in seiner ganzen Vielfalt, Baden-Baden.
Roggenhofer G (1903). Die Wäscherei in ihrem ganzen Umfange, 1. Auflage, Wittenberg.
Roggenhofer G (1914). Die Wäscherei in ihrem ganzen Umfange, 2. Auflage, Wittenberg.
Roggenhofer G (1927). Die Wäscherei in ihrem ganzen Umfange, 3. Auflage, Wittenberg.
Senf RM (1989). Saubere Sachen, Wiesbaden.
Walland H (1913). Kenntnis der Wasch-, Bleich- und Appreturmittel, Berlin.
Wasser, Werke (1998). 90 Jahre MEWA, Wiesbaden.

16.9 Appendix: additional information

The following sections contain additional information aside from the basic topic of this chapter.

16.9.1 Robert Koch Institute, Berlin

The Robert Koch Institute, RKI, is a German central control and research institution reporting directly to the German Federal Health Ministry. The Institute was founded in 1891 as the Royal Prussian Institute for Infectious Diseases and a place for Robert Koch to concentrate on research and development of tuberculin. In 1935 the Institute was affiliated to the Health Ministry of the German Reich and in 1942

© Woodhead Publishing Limited, 2011

converted into a German Reich institution. From 1952 to 1994 the Institute was part of the German Health Authority, newly founded after World War II. Since the Authority was subdivided again in 1994, the Institute is named after Robert Koch, the famous medical scientist and microbiologist. The textile services sector and the Robert Koch Institute are primarily linked via textile hygiene in healthcare.

16.9.2 German Health Authority List

There is a list of disinfectants and disinfecting processes approved and accepted by the Robert Koch Institute. Thermal and chemo-thermal processes are intended for disinfecting laundry in washing machines. Among the chemo-thermal processes there are mostly procedures with PCE compounds.

16.9.3 European and national directives for OR textiles

The European guideline for medical products 93/42/EWG of 14 June 1993 determines that OR textiles have to be regarded as medical products. In the law for medical products of 2 August 1994 and the amendments of 6 August 1998 and 1 January 2002 the regulations have been implemented into national law. In the CEN/TC 205/WG 14 the requirements for OR textiles have been discussed and defined at European level since 1997. A German committee has concentrated the national points of view and made them clear in the European circle. The results of the standardisation activities are published in DIN EN 13795 – 1 to 3. The aim is to ensure the necessary safety level for disposable and reusable products, i.e. OR gowns and drapes for patients during their life cycle.

16.9.4 Polyester microfibres

From the point of view of textile technology the use of textile laminates was a substantial progress in the field of OR textiles. However, one had to accept that the protective gowns were relatively heavy compared to those made of cotton or blended fabrics. Furthermore, it was not necessary that the surgical gowns were entirely watertight during simple operations or during those where few liquids were involved. As a result for these purposes microfibre gowns with a water-repellent finish were launched initially by the Swiss company Rotecno together with RENTEX. Later, further manufacturers joined them with similar products.

16.9.5 Physiological characteristics of protective surgical gowns

When in the 1970s the first GORE-TEX® gowns were tested, their clothing physiological properties were unknown. After all, the textile material was entirely

© Woodhead Publishing Limited, 2011

watertight, but was intended to be permeable to the moisture the wearer exuded. The Hohenstein Institute for Clothing Physiology carried out extensive trials for verification. Professor Dr Karl-Heinz Umbach tested the material with a skin model he had developed as well as with the manikin 'Charlie'.

16.9.6 The pros and cons of blended fabrics

The introduction of protective clothing for hospital personnel made of polyester–cotton blend fabrics instead of cotton was a time consuming process. Like all new things it was approved as well as rejected. The administration managers were in favour of it for cost concerns; while the personnel disapproved of it due to presumed reasons of a reduced wear comfort. In order to reach clarification, a large-scale test was run in 1971 with Hohenstein in charge. Nevertheless, the topic remained under discussion with a clear upward trend towards the mixed fabrics. In 1973 the Hohenstein Technical Academy drew up tender guidelines for the procurement of protective clothing made of polyester–cotton blend fabrics. Even today the pros and cons of blend fabrics or cotton are still under discussion.

16.9.7 Types of surfactants

Anionic surfactants are organic substances. When these surfactants are dissolved in water, negatively charged particles, i.e. anions, are created. These are the active washing component. In contrast, cationic surfactants ionise in water into the positively charged washing active cations and the non-washing active anions.

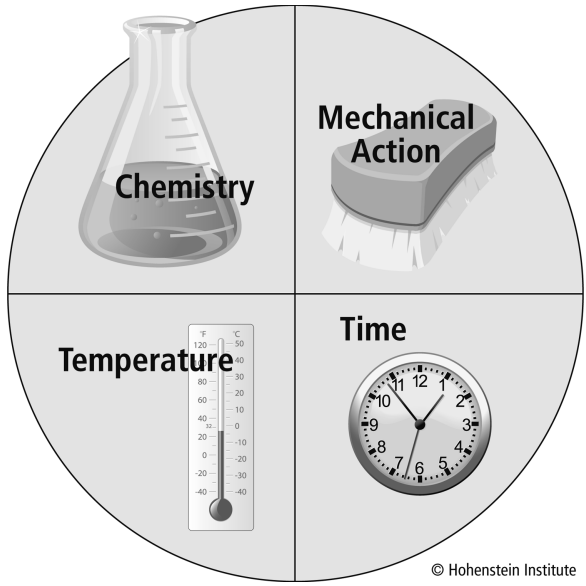
Non-ionic surfactants neither form cations nor anions in water. Their solubility in water is based on the binding of the hydrophilic parts to the water molecules.

'Surfactants' is the official name for surface-active compounds. The alternative word 'tensides' is derived from the Latin word 'tensus', 'tense' in English. In this case the surface tension of water is meant through which the water normally contracts to a drop and the wetting of surfaces is slowed down. Surfactants inhibit the surface tension and thus allow a quick wetting of surfaces.

16.9.8 Sinner's circle

The idea of Sinner's circle (Fig. 16.5) can be attributed to the scientific understanding and didactic abilities of Dr Herbert Sinner. After his studies at the Staatliche Akademie für Technik in Chemnitz and the Technische Hochschule in Dresden he first worked in the colour department of the German company IG Farbenindustrie Hoechst. Then he was employed for one and a half years as a scientific assistant at the German research institute of the textile industry in Dresden. During the following five years he worked for the rayon producing industry. In 1932 he started employment with the company Henkel & Cie. in Düsseldorf. There he dealt with textile washing procedures and improving the

© Woodhead Publishing Limited, 2011



16.5 Sinner's Circle: Chemistry, Mechanical Action, Temperature and Time.

washing results of mechanical washing devices. He published several papers and delivered lectures about the processes of removing dirt from textiles. He was naturally talented and could explain complicated procedures in a more simple way. In 1966 Herbert Sinner left the company Henkel due to age.

The effective cleaning performance of a laundry process is determined by individual factors being chemistry, mechanical action, temperature and time. Altogether they always amount to 100% or figuratively spoken they form a complete circle. If, for example, the laundering time is reduced, one or more of the remaining factors have to be increased in order to achieve the same cleaning performance.

© Woodhead Publishing Limited, 2011

17

Odour control of medical textiles

R. H. McQUEEN, University of Alberta, Canada

Abstract: Strong odours arising from the skin, from wounds, or as a result of incontinence are problematic and can be unpleasant for both the patients emitting odour and for those in close proximity with them (e.g. carers, family members). Some textiles have the potential to intensify odour generated through bacterial metabolism of secretions retained within the textile. However, textiles can also be used to control odour either through the absorption of odorous volatiles, the release of antimicrobial agents or the dispersal of scents. In this chapter, sources of human malodour, methods for measuring odour, and methods for controlling or reducing odour through textiles are discussed within the health care setting.

Key words: odour absorption, antimicrobials, sensory measurement, instrumental measurement, wound odour, body odour, microorganisms.

17.1 Introduction

Odour can be described as the 'property of a substance that is perceptible by the sense of smell' (Trumble and Stevenson, 2002). Sources of human body odour come from secretions from the sweat glands, urine, faeces, expiration, saliva, breasts, skin and sex organs. Healthy individuals can emanate strong odours due to a range of factors, such as their personal physiology, diet, physical activities and hygiene practices. An unhealthy individual may suffer further increase in unpleasant and strong body odour due to an imbalance in personal microflora, a difference in metabolic activity, problems with urinary or faecal incontinence and from the ingestion of therapeutic medicines. Malodour may also arise from wounds which have become infected or have necrotic and dying tissue. People emanating strong odours as a result of infected or dying tissue, incontinence or disease can become withdrawn, isolated and depressed as the malodours impact on their relationships with family and friends (van Toller, 1994).

Although tactics to control an individual's malodour should firstly involve addressing the source of the problem (e.g. oral or topical medication to reduce microbial infection, recommend changes in hygiene practices), textiles can also be utilised to reduce the intensity of malodours: through the absorption of odorous volatiles; incorporation of antimicrobial agents; or the masking of malodours by dispersing fragrances. Appropriate refurbishment procedures are required to effectively remove the soils and microorganisms which have been transferred to textiles during use, as well as the odorous compounds either transferred to, or generated within the textile substrate. Evaluation of odour controlling products can

© Woodhead Publishing Limited, 2011

be measured through sensory analysis (using the human nose) or through instrumental analysis (using instruments to detect the odorant concentration and/or structure).

17.2 Measurement of odour

Odour is detected through the sense of smell. In a hospital or other care facility, patients, health practitioners, friends and family members may all be able to detect the presence of unpleasant odours emanating from a patient's body, wounds, and soiled bedding and/or clothing. Sensory or psychophysical evaluation refers to the scientific approach of using human sensors for the systematic identification of the presence, intensity and/or quality of an odour or combination of odours. An alternative approach to testing for the presence of odour is through instrumental evaluation using chemical and/or electronic sensors to determine the concentration and type of odorous compounds in the air or within the textile substrate. Both approaches have their advantages and limitations. Antimicrobial efficacy tests are commonly used to measure or predict the likelihood of the build-up of odour in antimicrobial-treated textiles. The evidence does not however show that this type of measurement alone directly corresponds to odour control in textiles.

17.2.1 Sensory assessment of odour

Although the human nose is an imperfect instrument for creating and conducting standardised tests and assessments of objectionable odours, sensory evaluation is a scientific discipline used to evoke, measure, analyse and interpret reactions to those characteristics of materials/substrates as they are perceived by the senses of sight, smell, taste, touch and hearing (Stone and Sidel, 2004). The appropriate test method selection (e.g. paired comparison, scaling tests, ranking) is important as inadequate information may be gathered of the samples under evaluation. The sensory measurement of odour involves measurement of its quality and intensity.

Sensory test methods

Discrimination tests are used to determine whether at least two samples are perceived to be different from one another, and are most useful for detecting small differences between and among samples. Common examples of discrimination tests are: paired comparison tests; triangle tests; duo–trio tests; A-not-A tests; two-out-of-five tests (Lawless and Heymann, 1998).

Category scales involve a method of rating a stimulus by assigning a value to it. Usually this is on a numerical scale but can involve words or points on a line (Lawless and Heymann, 1998). An insufficient number of categories could render the scale unsuitable for distinguishing among many levels of stimuli, whereas, too many points may increase the likelihood of detecting differences which are not there (Lawless and Heymann, 1998).

© Woodhead Publishing Limited, 2011

Line scales (or visual analogue scales) require assessors to rate a sensation by placing a mark on a line which has been anchored at each end point by some form of descriptor (e.g. weak/strong, low/high). A perceived advantage of the line scale over the category scale is that assessors are less restricted by their choices as the line scale offers a 'continuously graded choice of alternatives' so potentially greater discrimination can be obtained (Lawless and Heymann, 1998).

Scaling is useful in sensory measurement when there is a need to quantify sensations by using either nominal, ordinal, interval or ratio scaling techniques (Stevens, 1951). Both category and line scales are useful in that they are suitable for diverse applications, simple to use, and easy to analyse statistically. Both are cost and time effective as they allow at least one data point for a single stimulus (Lawless and Heymann, 1998).

Ranking is the process of arranging three or more samples in order, based on some selected attribute (e.g. high to low), and is generally a forced-choice procedure, where ties are not allowed (Pangborn, 1984). Ranking is often used for preliminary screening to identify samples that may vary from the group. Ranks offer no measure of the size of difference between/among samples, and as straight comparisons are made among samples, there is no effective means of comparing samples from one session to another (Pangborn, 1984).

Magnitude estimation is the 'process of assigning values to the intensities of an attribute in such a way that the ratios between assigned values are the same as between the magnitudes of the perceptions to which they correspond' (International Organization for Standardization, 2008). As judgements are expressed in proportions, one scale can be compared directly with another. By using a common reference sample for each assessor, judgements are likely to be more reliable than those that may be influenced by some type of cross-comparison operative in category or line scaling (Pangborn, 1984). Magnitude estimation is most effective with stimuli that have moderate to large supra-threshold differences (Chambers and Wolf, 1996).

Examples of tests used in the evaluation of wound and body odours

When evaluating the improvement of odour due to the use of odour absorbing and/or antimicrobial treated textiles, it may be difficult to use discrimination tests *in vivo* as variation amongst patients will result in varying levels of odour intensity and quality (the latter may make distinguishing between samples confusing). Use of the matched-control sample (i.e. a treated or odour controlling dressing matched with a non-treated or regular dressing on wounds on the same patient) may be possible. However, to be statistically viable discrimination tests require a large number of assessors, which poses logistical challenges, as well as ethical, if odour assessment is carried out by directly assessing a wound rather than by assessing the textile substrate removed from the body. *In vitro* studies may lend themselves more easily to discrimination tests as an application of a certain concentration of an

© Woodhead Publishing Limited, 2011

odorant can be applied to a textile substrate, although this would not be applicable to textiles where odour control was only dependent on controlling bacterial populations. A category scale may be more applicable for assessing odour *in vivo*, but requires an adequate number of assessors being available to assess odours directly on patients. Complications due to differences in odour character or quality are still likely to be a problem. Nonetheless, a number of studies which have evaluated body odours either *in vitro* or *in vivo* are directly related to odour intensity remaining on textiles. A variety of category and line rating scales have been used to measure intensity of axillary or foot odour. A line scale (labelled from low to high) was used to measure odour intensity emitted from cotton, wool and polyester knit fabrics following wear against the male axillae (McQueen *et al*., 2007).

Different types of category scales have been used to evaluate wound odour in clinical settings by either the health practitioner or the patient. Various versions of a four-point category scale have been used in clinical trials; for example, no odour to foul malodour (Bowler *et al*., 1999); no odour, little, moderate and severe odour (Jørgensen *et al*., 2005); and none to severe odour (Karlsmark *et al*., 2003). Another common rating scale used for the assessment of wound odour in practice is the 'Odour Assessment Scoring Tool' (Poteete, 1993) which was adapted from a scale originally used by Baker and Haig (Baker and Haig, 1981; Haughton and Young, 1995) (Table 17.1). The advantage of this scale for clinical use is that it provides greater detail than many other rating scales do since the assessor's (practitioner's) presence relative to the patient and the dressing is inherent within the scale. This scale could be used for assessing improvement in odour over a treatment period (e.g. use of antimicrobial-treated dressings), but would be less appropriate for the evaluation of odour-absorbing dressings (such as activated charcoal dressings) in controlling malodour.

A wound odour measurement scale offering greater discriminatory ability was a 10 cm line scale labelled numerically along the scale from 0 to 10 (0 corresponding to 'no wound odour', 1–4 'mildly offensive', 5–8 'moderately offensive', 9–10

Table 17.1 Odour assessment scoring tool – or the Baker and Haig scale

Score	Assessment
Strong	Odour is evident upon entering the room (6–10 feet from the patient) with the dressing intact
Moderate	Odour is evident upon entering the room (6–10 feet from the patient) with the dressing removed
Slight	Odour is evident at close proximity to the patient when the dressing is removed
No odour	No odour is evident, even at the patient's bedside with the dressing removed

Source: Haughton and Young, 1995.

© Woodhead Publishing Limited, 2011

'extremely offensive') was used by an investigator and patient to monitor wound odour on a daily basis (Kalinski *et al*., 2005). However, it can often be difficult to view ratings as absolute, or to compare ratings across different times, sessions or settings as sensory measurement can be affected by the context in which a stimulus is assessed (Lawless and Heymann, 1998). The discriminative capability of the four-point scales in clinical trials used to assess improvement of wound odour will be adequate since the measures in wound healing are evaluated over a number of weeks.

As the human nose is an imperfect instrument for creating and conducting standardised tests and assessments of objectionable odours, test results are uniquely dependant on the odour acuity and consistency of the assessors. The terms 'expert' or 'experienced judge' have been used (Rennie *et al*., 1991; Taylor *et al*., 2003) often without further details on what constitutes being an expert provided. In some axillary odour trials assessors were reportedly selected on their odour acuity. Acuity to what compounds was not always made clear (e.g. Taylor *et al*., 2003), although odorants such as 5α-androst-16-en-3-one and 5α-androst-16-en-3α-ol were most frequently involved (Rennie *et al*., 1990; Zeng *et al*., 1991). Anosmia to these two compounds is quite common in a population (Amoore, 1977). However, people can also experience specific anosmia to other compounds common in axillary odour, such as 3-methyl-2-hexenoic acid (Baydar *et al*., 1992), which was the case with one of the four assessors in the study by Zeng *et al*. (1991). Only a few sensory trials evaluating body odour have reported details of the sensory analysis and level of training assessors received (e.g. Troccaz *et al*., 2004; Rennie *et al*., 1990).

In most clinical trials where wound odour has been included in the assessment of improvement of wound healing the assessor is usually a nurse, wound clinic practitioner or referred to as the 'study personnel' who presumably has expertise in caring for all aspects of wounds but may not be selected based on odour acuity (Holloway *et al*., 2002; Jørgensen *et al*., 2005; Münter *et al*., 2006; Karlsmark *et al*., 2003). In some trials, the patients themselves were required to evaluate odour either with or without an additional evaluation by a professional (Kalinski *et al*., 2005; Holloway *et al*., 2002; Jørgensen *et al*., 2008). Mention of a patient's olfactory acuity was not often made, although Holloway *et al*. (2002) did exclude patients with olfactory abnormalities (i.e. anosmia or hyposmia) from their study.

Qualitative description of wound and body odours

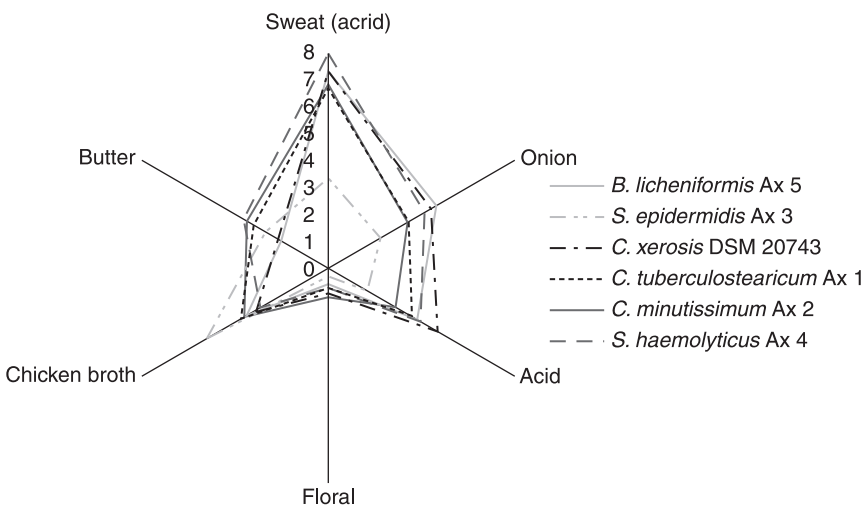
Descriptive analysis of odours is problematic in a number of ways. Panels of assessors may disagree on terms used to both quantify and qualify odours which can result in confusing and ambiguous findings. The terms 'typical' or 'classic' axillary odour have been applied in many studies identifying axillary odorants. For example, these terms were used by Rennie *et al*. (1990) in a study on the 16-androstene steroids, although as many as 50% of a population is anosmic to these steroids; and Zeng *et al*. (1991) found 'typical' axillary odour to be related to C_6–C_{11} fatty acids. One author defined axillary odour as being an 'offensive

© Woodhead Publishing Limited, 2011

pungent smell so typical of body odour' but later referred to a sample produced *in vitro* by micrococci as having a 'distinctive sweaty, acid odour'. Presumably this is different from the 'offensive pungent smells' and the 'apocrine odour' compared to the 'non-apocrine odour' (Leyden *et al*., 1981).

Odours emanating from fungating wounds from five cancer patients were described as having 'similar pungent sulfury odours', with wounds from three patients also emitting a slight odour of 'rotten fish' and wounds from the other two a 'cheese' odour (Shirasu *et al*., 2009). The presence of putrescine and cadaverine have been associated with a strong acrid odour and described as producing the gag reflex (van Toller, 1994). Sulfur-containing compounds, hydrogen sulfide, methanethiol, and dimethyl sulfide were described as 'rotten eggs', 'decomposing vegetables' and 'sweet', respectively, by two assessors who had shown good acuity to differentiating among sulfur gases (Suarez *et al*., 1998).

Work on bacterial suspensions incubated with axillary sweat extracts provide the most detailed attempt to classify the odour quality of body odorants (e.g. Troccaz *et al*., 2004). In this study, six descriptive terms were used (acid, chicken broth, onion, sweat (acrid), butter, floral) on an 11-point intensity scale from 0 (none) to 10 (very strong). A highly trained panel, consisting of a perfumer and 30 assessors, carried out the descriptive analysis. Using principal-component analysis (PCA) strong associations with sweat and onion, and sweat and acid were identified (Fig. 17.1) (Troccaz *et al*., 2004). This study was novel in providing a



17.1 Bacterially generated sweat–odour profiles. Olfactive evaluation of an expert panel of assessors. Radar graphic of the average values of intensity for each of the six descriptors; acid, floral, butter, sweat, onion, and chicken broth for each of the six strains after a 12 h incubation period on sterile odourless axillary sweat (Troccaz *et al.*, 2004).

© Woodhead Publishing Limited, 2011

qualitative analysis of axillary malodour notes. Although this *in vitro* study is still somewhat removed from the diversity and complexity of the human axillae, these methods for detecting odour, as well as generating odour, have potential to be applied to the measurement of body odour within textiles in a controlled setting.

17.2.2 Instrumental evaluation of odour

The physio-chemical approach to odour detection involves the instrumental analysis of the chemical structure and concentration of an odorant (Neuner-Jehle and Etzweiler, 1991). The relationship between the sensation of an odour as perceived by a human, and the physical or chemical properties of the odour is not as simple as other sensations such as colour or sound, where these can be related to known physical forms such as intensity and wavelength. Measurement of the odorant structure and concentration is possible through quantitative chemical analytical techniques. The ideal situation is to develop an instrument that is capable of replicating the human olfactory system without the added problems of human variability, sensitivity, and perception.

Approaches to measuring odorants on textiles

Typically, two approaches are taken to measuring the presence and concentration of odorants on textiles: direct analysis of a textile substrate; or analysis of the headspace above a sample. Direct analysis of the textile substrate, usually involves a multi-stage process of extraction and clean-up before sample analysis using gas chromatography–mass spectrometry (GC-MS) analytical techniques (e.g. Bird and Gower, 1982; Preti *et al*., 1987). The ability of the human nose to detect a compound in the air is related to the volatility of that compound. Therefore, the applicability of this approach to measuring odour from absorbent textiles which absorb greater quantities of malodour (e.g. activated charcoal dressings) may be questionable. Another inherent problem with directly measuring a sample only is that some compounds not important in the odour mix could be predicted as being important. Furthermore, many volatile compounds can be non-odorous, or have high odour thresholds, so are not important in human olfactory perception. Coupling gas chromatography techniques with olfactometry (GC-O) is a useful way to determine odour-active compounds in a substance (e.g. Boscaini *et al*., 2003; Zeng *et al*., 1991). GC-O has been applied successfully for many years, albeit still reliant on the human as the odour-detecting instrument.

Direct measurement and associated GC-MS techniques have been used for determining odorous compounds considered important in axillary malodour. Determination of odorous compounds in axillary secretions has involved solvent extraction of cotton or ‘unspecified’ pads (or by directly swabbing the axillary vault with a solvent), followed by hydrolysis and acidification before GC-MS analysis (Zeng *et al*., 1991; Natsch *et al*., 2003). Although these studies were

© Woodhead Publishing Limited, 2011

specifically isolating the compounds important in malodour (which tended to be acidic) this process of separating secretions into acidic fractions may have resulted in some important basic and neutral odorants being overlooked. For example, many esters, ketones and, in particular, aldehydes were identified to be the main contributors to the odour profile of washed garments previously soiled with sweat and sebum (Munk *et al*., 2000).

Analysis of the headspace above a sample is an alternative to direct measurement and chemical extraction techniques. Instrumentation for detection of headspace volatiles include an array of gas sensors (electronic noses), on-line real time chemical ionisation apparatus (e.g. PTR-MS, SIFT), and trapping devices for GC-MS analysis.

Electronic noses

Several instruments known as electronic noses have been developed, which typically consist of an array of gas-sensitive semi-conductors connected to an appropriate pattern-recognition system. Electronic noses have the capability to detect complex odours. They can have up to 40 sensors, each calibrated for a different chemical specificity, which, when combined provides a measurement pattern. The electronic nose relies on pattern recognition and therefore cannot identify unknown (or unexpected) compounds.

Common types of chemical sensing arrays are metal oxides sensors (e.g. tin oxide detectors), conducting polymers (e.g. polypyrrole films) and piezoelectric sensors (Persaud, 2005). Tin oxide detectors have many 'nose' applications and are capable of detecting a large number of organic volatiles. However, high temperatures (300 to 400°C) are typically required to operate the devices, which make them costly to run and the elevated temperatures lead to a risk of the volatiles breaking down at the sensor surface (Persaud *et al*., 1996). Quartz resonator and surface acoustic wave devices consist of a piezoelectric substrate coated with a sensing membrane. Conducting polymers, derived from aromatic and heteroaromatic materials, measure the resistance changes in the semi-conducting film.

Electronic noses have been applied in the food industry for quality control and detection of contaminants and off-odours (e.g. Persaud *et al*., 1996; Frank *et al*., 2001), in environmental monitoring of livestock waste (e.g. Persaud *et al*., 1996), sewage treatment works (e.g. Stuetz *et al*., 1999) and in the medical field for analysing bacterial metabolites (e.g. Bailey *et al*., 2008). In the medical field electronic noses so far may be applied to measuring improvement in wound odours over a period of time rather than effectively measuring the odour-controlling capacity of a particular textile. For example, the dressing itself has been used as a medium for collecting odours and then placed into a container or bag, allowed to equilibrate and then assessed via drawing the odour across the sensors (Parry *et al*., 1995; Greenwood, 1997). However, the human nose is often

© Woodhead Publishing Limited, 2011

more sensitive to odorous compounds than are instruments used to detect odours, as illustrated in the analysis of compound from pig slurry (Persaud *et al*., 1996).

Chemical ionisation in real-time analysis

Instruments utilising the concept of chemical ionisation allow real-time analysis without the necessity for preconditioning or complex extraction; they avoid the fragmentation of organic molecules that occur with electron impact ionisation. The proton transfer reaction mass spectrometer (PTR-MS) and selected ion flow tube mass spectrometer (SIFT-MS) both use chemical ionisation within a flow drift tube (Lindinger *et al*., 1998; Spanel and Smith, 1996). Unlike conventional electron impact ionisation, chemical ionisation does not undergo strong fragmentation, therefore, chemical ionisation is a preferable technique for detecting volatile organic compounds when a mixture of gases is to be analysed. A quadrupole mass filter is required for SIFT-MS but not necessary for PTR-MS since H_3O^+ is the only reactive ion. As PTR-MS and SIFT-MS technologies are used for on-line monitoring of compounds and not predominantly for gas analysis, the use of GC-MS methods for complete compound identification is usually recommended (Lindinger *et al*., 1998).

Applications using chemical ionisation technology have been successfully used in detecting carboxylic acids in axillary odours (e.g. von Hartungen *et al*., 2004). Both SIFT-MS and PTR-MS can be used to identify several trace gases in a sample, potentially providing a 'fingerprint' of the compounds present, and by selecting gases known to be present can also be used to analyse changes in concentration over time (Spanel and Smith, 1996; Lindinger *et al*., 1998). PTR-MS was used to detect axillary odorants emitted from fabrics (McQueen *et al*., 2008). Although, GC-MS was not used to verify specific compounds, based on their molecular weight, compounds likely to be short-chain fatty acids were detected. However, the PTR-MS did not detect any medium-chain fatty acids which are also suspected of being major contributors to overall axillary malodour (McQueen *et al*., 2008).

17.2.3 Antimicrobial efficacy tests

Measuring the effectiveness of antimicrobial properties in reducing bacterial counts, or preventing microbial growth, is an indirect method for measuring or predicting the reduction of odour or prevention of odour build-up on textiles. Claims of odour reduction may be made based on the reduction in bacterial numbers often following a standard test method such as AATCC 100. There is the potential for odour control due to antimicrobial treatments, however, using only antimicrobial efficacy tests as a method to assess odour reduction is not appropriate.

Most antimicrobial efficacy tests measure bacterial growth *in vitro* and involve either the quantitative or qualitative measurement of bacterial populations. Quantitative measurements include absorption or suspension tests where the

© Woodhead Publishing Limited, 2011

quantity of bacteria inoculated onto treated and untreated test specimens is assessed at '0' contact time and at times following incubation at selected time intervals. Tests such as AATCC 100, ISO 20743-Method 10.1, measure the reduction in bacteria after incubation after a specified length of time, often 24 or 18 hours under static conditions (International Organization for Standardization, 2007; American Association of Textile Chemists and Colorists, 2004). An alternative approach which evaluates the antimicrobial efficacy under dynamic conditions is the ASTM E 2149 (American Society for Testing and Materials, 2001).

Test organisms such as *Staphylococcus aureus* and *Klebsiella pneumoniae* are specified for the Gram positive and Gram negative test organisms respectively. Although these test organisms are known pathogens, they are not responsible for generating odour through the metabolism of human sweat. Odour causing bacterial species should be tested against the *Bacillus* species, which has been one strain identified in foot odour which may be resistant to antimicrobial-active textiles (McQueen *et al*., 2010).

17.3 Key issues of odour control in medical applications

17.3.1 Sources of odour

Sources of odour vary considerably. In the context of medical applications there may be many odours associated with the treatment of patients such as disinfectants, drugs, or use of machinery which can affect air quality around the patient; however, only odours deriving from the patient will be discussed in this chapter.

Body odours emanating from human skin

Individuals will, of course, vary in odour intensity from one another as some people may naturally be more odoriferous than others, a difference which could be further exasperated by poor hygiene and/or health. While there are distinctive odours that can be associated with various diseases and syndromes (Senol and Fireman, 1999), the main physiological contributors to body odour come from eccrine and apocrine sweat glands located in the axillary region, sternum, anogenital area, mammary areolae, eyelids, scalp, ear canals, feet and hands (Henkin, 1995). Secretions from the sebaceous glands, found in many of these same areas, also contribute to odour. Odour produced by the body can be strengthened by ingesting foods such as garlic, onions, alcohol, as well as some therapeutic drugs (Henkin, 1995; Labows and Preti, 1992). Although all parts of the skin can emit odour to some degree, the body sites most typically responsible for emanating (potentially) strong odours are the axillae (underarm), foot and anogenital regions.

The axilla is a site of high odour production because of the high density of apocrine sweat glands, and high density of bacteria living in this site. The eccrine

© Woodhead Publishing Limited, 2011

glands in the axillary region also provide a moist environment for bacterial metabolism, although high eccrine sweating does not necessarily equate to high axillary malodour. The protein-rich secretions of the apocrine and sebaceous glands consist of cholesterol, other steroids and long-chain fatty acids (Labows, 1988), and it is through the biotransformation of these secretions that axillary malodour is generated. The array of compounds that constitute axillary odour is considerable, and generally consist of compounds which come under one of three generic groups: 16-androstene steroids (Bird and Gower, 1982); short-chain and medium-chain fatty acids (Zeng *et al*., 1991), and volatile sulfur compounds (VSC), the sulfanylalkanols (Troccaz *et al*., 2004; Natsch *et al*., 2004) responsible for sulfury notes in axillary malodour.

The foot has a moist environment due to a high density of eccrine sweat glands and therefore supports high numbers of bacteria. Short-chain carboxylic acids have been found to be the main volatiles responsible for high foot odour, with isovaleric acid being present in all subjects who were considered to have foot odour but not present in those without foot odour (Kanda *et al*., 1990; Ara *et al*., 2006).

In healthy individuals genital malodour is not common. However, strong odours may be associated with discharges from the vagina when there is an infection or imbalance of vaginal microflora. Concentrations of short-chain fatty acids have been found to increase in women exhibiting bacterial vaginosis, as well as the presence of polyamines, particularly putrescine and cadaverine (Cook *et al*., 1992; Chen *et al*., 1979).

Odours associated with human waste

Gases from human waste products such as faeces and urine are possible causes of malodour. Although a number of volatile compounds are present in urine; fresh urine typically does not have a strong odour unless it is due to certain dietary intakes or some diseases (Zlatkis *et al*., 1981). Stale urine, on the other hand, can become malodorous when ammonia is produced during the bacterial metabolism of urea (Louhelainen *et al*., 2001).

Acidic, sulfurous and nitrogen volatiles may make up the odours emanating from faeces (Sato *et al*., 2002). Fatty acids such as acetic acid, propionic acid, butyric acid and isovaleric acid have been found to increase in concentration in faeces from people experiencing diarrhoea (Sato *et al*., 2002). Hydrogen sulfide and methyl mercaptan, although present in small concentrations in faecal matter, are still considered to be a significant component of overall malodour. Furthermore, the presence and concentration of hydrogen sulfide has been found to be highly correlated with intensity of flatus malodour (Suarez *et al*., 1998).

In healthcare facilities the likelihood of urinary incontinence or loss of bowel function is common, particularly in critical care and geriatric facilities. Textile products such as bedding, underwear and incontinence products can become contaminated with urine or faecal matter, and unless appropriately managed, will

© Woodhead Publishing Limited, 2011

emanate malodours. Adults who experience incontinence in their daily lives to varying levels of severity, fear that leakage and odour will be detected by others (Lagro-Janssen *et al*., 1992; Fader *et al*., 2008).

Odours arising from wounds

The majority of wounds heal without difficulty and do not emit unpleasant odours. However, chronic wounds such as fungating tumours, pressure ulcers, other infected wounds, and those with sloughy or necrotic tissue which may resist healing, can have a strong malodour associated with them (Grey *et al*., 2006; Kalinski *et al*., 2005; Collier, 2000). The presence of malodour in a wound is typically an indication that the wound is infected as the odour emitted from healthy wounds is generally less offensive (Williams and Griffiths, 1999). A range of tissue types may be present in fungating wounds (i.e. muscle, fat, skin) as well as devitalised or necrotic tissue. The type of tissue present in a wound, as well as the range of anaerobic, aerobic bacteria, and metabolic volatile by-products which may be present, will affect the odour emanating from the wound (Moody, 1998). Volatile fatty acids, such as propionic, isovaleric and valeric, isobutyric and butyric acids may be released during metabolism of lipids (Moody, 1998; Collier, 2000; Dankert *et al*., 1981). Volatiles such as putrescine and cadaverine are also common odours emitted from putrid wounds which can evoke a gagging response (van Toller, 1994). Wound exudate, particularly stagnant exudates, may also result in malodour.

17.3.2 Microorganisms

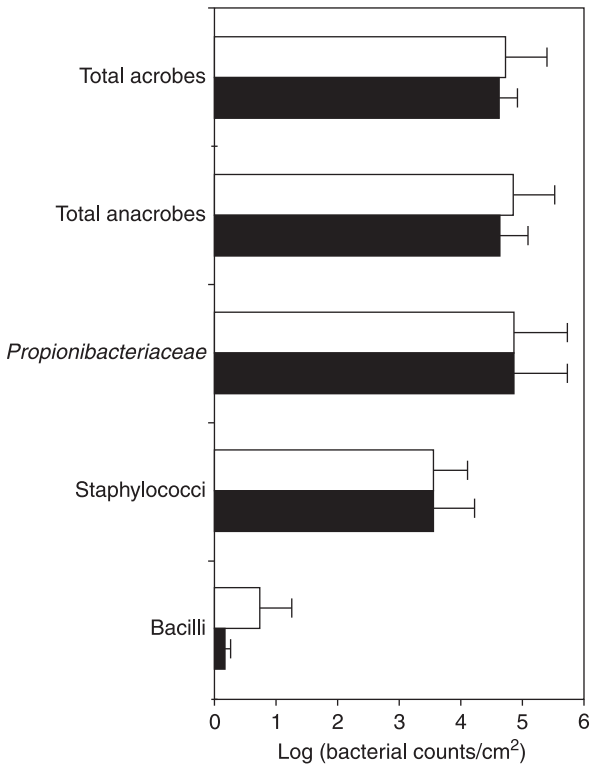
Most malodours emanating from the skin, wounds and bodily waste products are a result of microbial metabolism of proteins, lipids and/or carbohydrates. As most bacteria thrive in high moisture environments, the axillary, foot and groin regions are typically associated with high bacterial populations in comparison to other areas of the skin. High bacterial loads are usually required for odour to be generated from the skin or from wounds. A wound is considered to be infected when the microbial colonisation is 10^6 colony forming units (cfu) per gram of tissues or greater (Jackson, 2001). Two strains of corynebacteria capable of producing axillary odour incubated on ether axillary extracts, did not become odorous until after the population density reached $10^5/cm^2$ and $10^6/cm^2$ (Rennie *et al*., 1991). Also, no improvement in patient's bromidrosis (i.e. foul-smelling perspiration) was noted when bacterial populations (mostly diphtheroids) remained above 10^4 cfu/cm^2 (Guillet *et al*., 2000).

Aerobic bacteria are more often responsible for malodours emanating from the skin, such as from the axillae or feet. The axillary microflora tend to be dominated by *Staphylococcus* or *Corynebacterium* species, with *Propionibacterium* and *Micrococcus* species also present (Taylor *et al*., 2003; Kloos and Musselwhite, 1975; Rennie *et al*., 1990). However, it is the aerobic corynebacteria that have

© Woodhead Publishing Limited, 2011

been implicated as the main cause of axillary malodor (Taylor *et al*., 2003; Rennie *et al*., 1990). The foot is predominately populated with staphylococci, corynebacteria, and micrococci (Marshall *et al*., 1987). High numbers of both corynebacteria and staphylococci were associated with high foot odour, with no type of organism isolated as being the main contributor to odour (Marshall *et al*., 1988). In a later study, the genus *Bacillus* were found to be in higher numbers on persons exhibiting strong foot odour, despite being relatively low in prevalence in general (Ara *et al*., 2006) (see Fig. 17.2).

While both anaerobic and aerobic microorganisms are often present on malodorous wounds, it is the anaerobic bacteria that have been implicated in



17.2 Relationship between the average number of bacteria and foot odour. Open bar: Bacteria isolated from the plantae of subjects with foot odour judged to be level 3 or higher by a sensory test. Solid bar: Bacteria isolated from the plantae of subjects with foot odour judged to be level 2 or lower by a sensory test. In 96 healthy individuals, the odour level of the planta was evaluated by a direct sensory test using a five-point scale, and the subjects were divided into those at level 3 or above and those at level 2 or below. (Ara *et al.*, 2006) © 2008 NRC Canada or its licensors. Reproduced with permission.

© Woodhead Publishing Limited, 2011

causing wound malodour (Altemeier, 1938; Hampson, 1996). *Bacteroides* species have often been associated with infected odorous tumours and wounds, although their presence has also been detected on non-odorous tumours (Hampson, 1996). Despite anaerobic bacteria always being present in malodorous wounds it appears that an interaction between anaerobic and aerobic bacteria are necessary for malodour to occur. As Bowler *et al*. (1999) found that malodour was most often associated with the presence of both anaerobic and aerobic microorganisms but not when only aerobic bacteria were responsible for the infection. *Bateriodes* species, pigmented and non-pigmented Gram-negative anaerobes, *Prevotella* species and *Porphyromonas* species were strongly associated with malodour. It was less clear as to whether or not *Peptostreptococcus* species, which was present in high numbers on both malodorous and non-odorous wounds, was responsible for odour (Bowler *et al*., 1999). Mixed colonies with β-haemoltyic streptococci were identified from 14 of 24 patients with venous leg ulcers, and identified as having a unique odour profile as detected by an electronic nose (Parry *et al*., 1995).

17.3.3 Textiles

Textiles or fibrous materials used in hospitals are classified into either multiple-use (reusable) or single-use (disposable). Multiple-use textiles must be appropriately decontaminated, and depending on the application, completely sterilised (e.g. surgical drapes) before repeated use. Typically, multiple-use textiles are woven or knitted and may in some cases be a composite material with a film laminate or coating also applied. Single-use products tend to be constructed of nonwoven fibrous materials and/or films. Products which may be used in close proximity to wounds (e.g. dressings), or during surgical procedures, need to be sterile and low-linting to reduce the likelihood of microorganisms or foreign particles causing wound infection. Single-use products that have retained odour can be disposed of but removal of odours from multiple-use products must be carried out through appropriate decontamination techniques.

Textiles can contribute to malodour; moist textiles provide an excellent environment for growth of microorganisms. Within the medical and health context the relationship between odour and textiles can be grouped into two categories. The first is the prevention of odour build-up within textiles (e.g. sweat or other human secretions or excrement in bedding and clothing); and the second is the control of odour through the use of textiles (e.g. bandages and dressings, incontinence products, flatus devices).

Many absorbent textiles are composed of inherently hydrophilic fibres such as regenerated cellulose or cotton. Superabsorbent gels may be used in the construction of absorbent hygiene products. However, moisture absorbent textiles may also absorb these odorous compounds. The adsorption of lipids to the fibre surface of hydrophobic polyester or polypropylene fibres provide an excellent source of nutrients for some bacterial strains.

© Woodhead Publishing Limited, 2011

17.4 Control of odour with textiles

Odour control within reusable textiles and disposable nonwoven products generally take one of three forms: (i) control of bacteria and fungi which cause malodour; (ii) absorption/adsorption of odorous volatiles; and (iii) dispersal of scents to mask the malodour. For reusable textiles, malodour as well as the soils which may act as precursors to malodour and bacteria may be removed through appropriate refurbishment methods.

17.4.1 Antimicrobial textiles

Antimicrobial agents incorporated into textiles work either by killing microorganisms or inhibiting their growth on, or in, the textile. Most antimicrobial agents used in textiles are biocidal (i.e. kill microbes) and act by either damaging the cell wall, altering the cell membrane permeability, denaturing proteins or inhibiting or altering essential functions of the microorganisms' metabolic pathways (Gao and Cranston, 2008). Common antimicrobial agents used in textiles are silver, tricoslan, polyhexamethylene biguanides (PHMB) and quaternary ammonium compounds (QACs). The primary objective of an antimicrobial in a textile is typically to inhibit the growth of, or to kill microorganisms within the textile, rather than influence the resident or non-pathogenic skin microflora of the person wearing/using the textile. Therefore, unless the antimicrobial does leach from the textile, complete control of human body odours may not be possible since the treated textile may only control odour development within the textile but not that developed on the skin or other areas on the body. Nonetheless, reducing odour build-up within textiles may still be necessary since odour originating on the body and odour emitted from textiles in contact with the body can differ in quality and intensity. These differences can result from variations in humidity, temperature, airflow, nutrients and presence of antimicrobial agents on the skin and textile (Dravnieks *et al*., 1968).

Since microorganisms are primarily responsible for the majority of human malodours, it is surprising just how few studies have been done which link odour intensity with antimicrobial efficacy of treated textiles. Some studies, not specifically health related, have been conducted which relate a reduction or improvement of odour or odorous volatile organic compounds (VOCs) on textiles to a reduction in bacterial populations (Payne and Kudner, 1996; Mao and Murphy, 2001; Obendorf *et al*., 2007). In the medical area a few studies have been done which relate the use of antimicrobial-treated wound dressings to an improvement of odour and wound healing (Jørgensen *et al*., 2005; Münter *et al*., 2006). The overall lack of research in this area may be due to the fact, that for medical applications, antimicrobial-treated textiles tend to be relevant for reducing the spread of infection or disease due to the transmission of bacteria or viruses (e.g. Borkow and Gabbay, 2008) rather than reducing or controlling odours. Most studies therefore only focus on reducing potentially pathogenic organisms *in*

© Woodhead Publishing Limited, 2011

vitro. In clinical trials or other *in vivo* studies which evaluate effectiveness of antimicrobial-treated wound dressings, the focus is on other parameters related to wound healing (e.g. size, pain, exudate) rather than specifically addressing or even mentioning improvement of malodour.

Although research by Payne and Kudner (1996), Obendorf and colleagues (2007) and Mao and Murphy (2001) does not specifically relate to apparel or textiles worn/used for health-related applications, their findings may have some merit here as the types of antimicrobials evaluated and the fibre content of their fabrics may still be present in hospital clothing/bedding (e.g. cotton, polyester and cotton/polyester blends). Payne and Kudner (1996) reported that no odour was detected when a 0.2% PHMB hydrochloride solution was applied to cotton towelling. This lack of odour corresponded to *Staphylococcus aureus* strains being recovered from the towelling after 24 hours incubation at 37°C somewhere less than 10^5–10^6 cfu/ml. At concentrations of 10^8 cfu/ml a strong pungent odour emanated from untreated nonwoven cotton wipes, whereas the wipes treated with varying concentrations of PHMB (i.e. 48, 184, 552 ppm) either did not show an increase in bacterial numbers or reduced bacterial populations following incubation (Payne and Kudner, 1996). *S. aureus*, although a potential pathogenic organism commonly found on many people, has not been associated with malodour *in vivo*. Instead, high numbers of corynebacteria are associated with malodour in the axillary region and bacilli in the foot region (Taylor *et al*., 2003; Ara *et al*., 2006).

Obendorf and colleagues measured the amount of 5α-androst-2-en-17-one (A-17-one) following incubation of a strain of *Corynebacterium striatum* with androsterone sulfate on polyester fabrics treated with 0%, 0.5% and 1% silver zirconium phosphate (Obendorf *et al*., 2007). The presence of androsterone sulfate was to represent a precursor for A-17-one odour. A reduction of A-17-one was observed as the concentration of silver zirconium phosphate increased on fabrics. Although this work provides some indication that odour production can be controlled within fabrics due to presence of antimicrobial agents, it does not represent real-world situations where odour may be produced on the skin and the odorous compounds subsequently transferred to the fabric. Furthermore, the compound A-17-one represents only one of the many axillary odorants emitted from the human axillae.

Mao and Murphy (2001) carried out a wear trial on fabrics (fibre content not reported) treated with Tinosan AM 100 a triclosan based antimicrobial. In a double-blind study 20 participants (12 males, 8 females) wore a fabric under each armpit. The participants were instructed to assess the odour emanating from the fabrics at four specific intervals (i.e. 7 hours after wear, 16 hours of storage, after a second 7-hour wear period, after a second 16-hour storage period). In 90% of all evaluations the participants reported to 'prefer' the treated fabrics compared to the untreated fabrics (participants were not aware which were treated and untreated), and reportedly the treated fabrics were perceived to be 'fresher' (Mao and Murphy, 2001). A 2–3 log decrease in *S. aureus* and *Klebsiella pneumoniae* was apparent after 24 hours of incubation at 37°C from both Tinosan AM 100 treated nylon fabric and blended 50%

© Woodhead Publishing Limited, 2011

cotton/50% polyester fabric (Mao and Murphy, 2001). Although examination of bacterial counts from the *in vivo* study was not carried out and the sensory test procedure used did not allow intensity of odour to be quantified, this study is one of the few antimicrobial-treated textiles studies to actually include a wear trial to assess whether an improvement of odour is associated with antimicrobial activity.

Incorporation of antimicrobial agents into dressings for wounds is common as the antimicrobial dressing acts either to reduce bacterial load in the wound or to reduce the adherence and growth of bacteria on the wound dressing itself. The reduction of microbial loads in wounds is beneficial to the process of wound healing as well as the removal of organisms that cause malodour. Silver is the most common antimicrobial agent incorporated into wound dressings. Iodine-based and PHMB gauzes or dressings are also available (Morin and Tomaselli, 2007; Michaels *et al*., 2009).

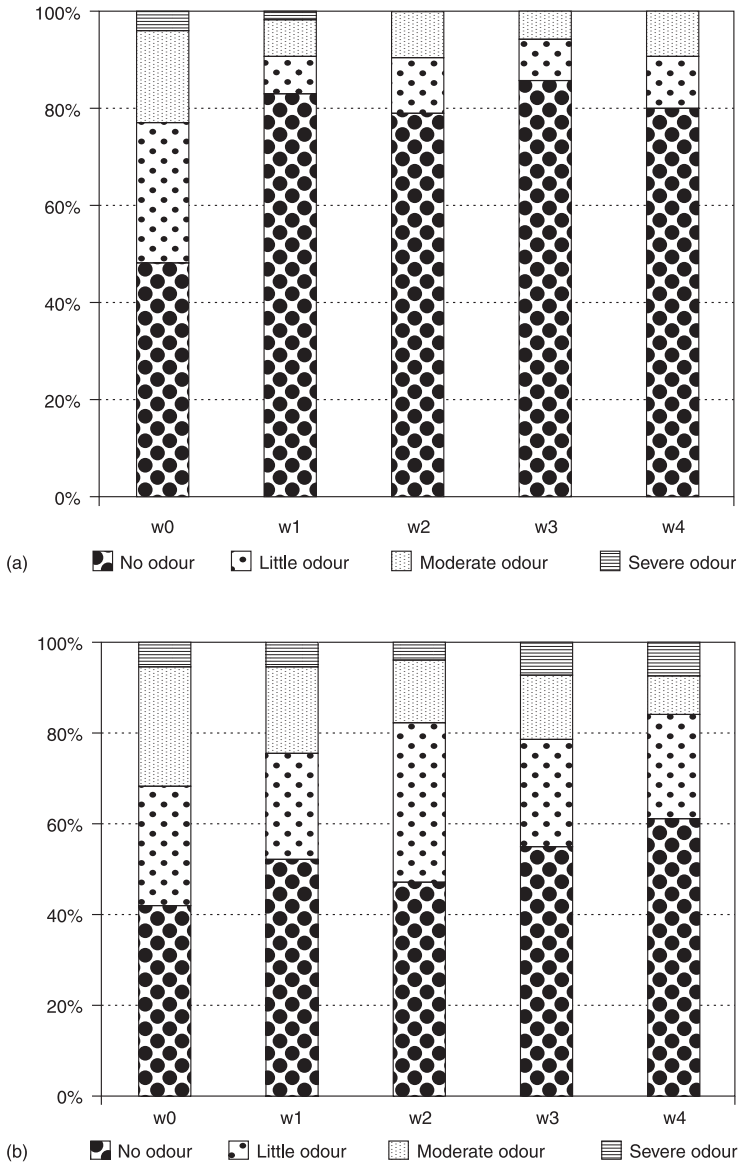
A number of *in vitro* studies report the efficacy of silver incorporated into dressings with varying levels of biocidal activity, mostly related to the characteristics of the carrier dressing and the delivery of the silver to the wound (Thomas and McCubbin, 2003; Mooney *et al*., 2006; Parsons *et al*., 2005). There are also *in vivo* trials which examine the effectiveness of silver dressings – in use – on wound healing (Jude *et al*., 2007; Tredget *et al*., 1998; Innes *et al*., 2001, Michaels *et al*., 2009). The focus of most clinical trials are on whether wound healing is progressing or improving; the presence and/or improvement of malodour, if mentioned at all, is only secondary to healing (Innes *et al*., 2001; Michaels *et al*., 2009; Jørgensen *et al*., 2005).

A large clinical trial was conducted which compared silver donating dressings (Aquacel Ag, Acticoat, Acticoat 7, Acticoat Absorbent Contreet Foam, Urgotul SSD) with non-antimicrobial dressings ($n = 208$) on patients with active ulceration of the lower leg (Michaels *et al*., 2009). Healing at 12 weeks following the beginning of the trial was assessed with no significant differences being detected in the improvement/healing of leg ulcers, whether a silver-donating dressing or a conventional dressing was used. Fifteen per cent of the silver-dressing group and 11.3% of the non-antimicrobial group reported having odorous ulcers at the beginning of the trial; however, the authors did not specifically report whether odour was improved during the duration of the study (Michaels *et al*., 2009).

Two large clinical trials were conducted to examine the effectiveness of the silver-impregnated hydrophilic foam dressing Contreet Foam (Coloplast) in improving wound healing and reducing wound odour (Jørgensen *et al*., 2005, Münter *et al*., 2006). In a comparative study, the effectiveness of Contreet Foam was evaluated against a hydrophilic polyurethane foam dressing (which did not have antimicrobial properties (i.e. Allevyn Hydrocellular dressing, Smith & Nephew) for improving healing of chronic venous and/or arterial leg ulcers (Jørgensen *et al*., 2005). One hundred and nine patients participated in the study and were randomly assigned to the Contreet Foam ($n = 52$) or the Allevyn Hydrocellular dressing ($n = 57$). Evaluations of the leg ulcers were carried out weekly over a four-week period by 'study personnel'. Among other indicators of

© Woodhead Publishing Limited, 2011

wound healing (e.g. amount of exudates, pain, ulcer size) odour was subjectively evaluated by rating odour on a four-point scale (i.e. no odour, little odour, moderate odour, severe odour) immediately following removal of the dressing (see Fig. 17.3). At the beginning of the study 52% (27/52) of the Contreet Foam group



17.3 Level of odour from the wounds treated with Contreet Foam (a) and Allevyn Hydrocellular (b) as evaluated by the study personnel at the weekly visits just after dressing removal (Jørgensen *et al.*, 2005).

© Woodhead Publishing Limited, 2011

had malodorous ulcers compared with 58% (33/57) of the non-silver dressing group. At the end of the first week a significant improvement in odour was noted for the Contreet Foam group with only 17% (9/52) reportedly having odour, whereas 47% (27/57) of the non-silver group were reported to have odour. In the remaining three weeks of the trial none of the ulcers dressed with the Contreet Foam were rated as severe in odour, whereas by week 4 about 40% of leg ulcers dressed with the non-silver dressing still had odour present and at least three to five of the patients had 'severe odour'. Patient questionnaires were completed for 'quality of life' and after one week only 6% of patients in the Contreet Foam group expressed concern with odour, whereas 21% of the non-silver group expressed concern with odour (Jørgensen *et al*., 2005). In the second clinical trial, Contreet Foam dressings were compared with routine local practice of managing infected wounds (n = 619), some of which included using antimicrobial active dressings. Reportedly, malodour reduced more rapidly in the patients who were dressed with Contreet Foam wound dressings than the local practice (Münter *et al*., 2006).

17.4.2 Odour-absorbing textiles

Activated charcoal

The purpose of antimicrobials in medical textiles such as wound dressings, is to either prevent infection from occurring or to contribute to the healing of infected wounds and odour control is a subsidiary effect; whereas, the inclusion of activated charcoal in wound dressings is specifically to manage odour. Activated charcoal cloth (or activated carbon cloth), made from the combustion or thermal decomposition of carbon containing substances, is highly porous and due to its large surface area, and chemical structure (predominately carbon but also associated with certain amounts of oxygen, hydrogen and some types may even include nitrogen), has the capacity to adsorb many gases and liquids. Textiles made from activated charcoal cloth or granules are used for absorbing malodours and used in wound dressings, incontinence products and flatus devices (Ohge *et al*., 2005; Thomas *et al*., 1998). Examples of commercially available activated charcoal dressings are described in Table 17.2.

Dressings which contain activated charcoal cloth have been found to be more effective than dressings without activated charcoal for controlling malodour emitting from wounds (Lee *et al*., 2007; Thomas *et al*., 1998). Since only the odour is absorbed, the dressings themselves may not have an effect on the cause of the malodour (i.e. bacteria). However, bacteria and their spores reportedly adsorb to the activated charcoal fibres in Actisorb Silver dressings where the charcoal then traps the bacteria for the antibacterial silver to 'produce structural changes in the bacterial cells leading to bacterial death' (Jackson, 2001).

When activated charcoal materials are coupled with an absorbent component to absorb and manage fluid in the dressing, odour reduction is improved

© Woodhead Publishing Limited, 2011

Table 17.2 Examples of odour-controlling activated charcoal based wound dressings

Dressing	Company	Description
Actisorb Silver 220	Johnson & Johnson Medical Ltd	Primary wound dressing; activated charcoal cloth impregnated with 0.22% silver contained within a spun-bonded nylon sleeve. Has no liquid absorbent capabilities but is designed to allow fluid to pass through dressing into an absorbent secondary dressing as required.
CarboFlex	ConvaTec Ltd	A multi-component, non-adhesive dressing with an absorbent wound contact layer. Activated charcoal cloth is positioned behind a layer of absorbent fibres (alginate/carboxymethyl cellulose fibres) and a perforated plastic film which provides unidirectional flow of liquid. Another absorbent layer and plastic film is positioned behind the activated charcoal fibres. Self-contained dressing for shallow wounds, or a secondary dressing for deep wounds. Odour management in wet wounds is enhanced due to the absorbent components.
Carbonet	Smith & Nephew	Primary dressing which can be used with or without a secondary dressing; multi-component dressing with a wound contact layer composed of knitted viscose rayon which is backed by an absorbent cellulosic layer, and bonded to activated charcoal cloth sandwiched between two layers of polyethylene net; good fluid handling properties.
CliniSorb	CliniMed	Activated charcoal cloth sandwiched between layers of viscose rayon with a nylon coating. Recommended to be used as a secondary dressing.
Lyofoam C	Mölnlycke Health Care	Direct contact dressing held in place with additional tape or bandage; a layer of activated charcoal cloth between a hydrophilic polyurethane contact layer and a hydrophobic polyurethane outer layer; good fluid handling capabilities as absorbent polyurethane sheets absorb wound exudates.
Pharmapad Carbon	Pharma-plast Ltd	Secondary dressing; composed of three layers, activated charcoal cloth sandwiched between two layers of viscose/nylon 'thermal bond' nonwoven; fluid absorbing dressing.
Sorbsan Plus Carbon	Unomedical Ltd	A multi-layer activated charcoal dressing with a calcium alginate skin contact layer with a secondary absorbent layer.

(Thomas *et al*., 1998; Lee *et al*., 2007). Thomas *et al*. (1998) compared the effectiveness of five commercially available wound dressings on limiting the movement of an odorous volatile diethylamine into the surrounding environment (Thomas *et al*., 1998). Four of the five dressings contained activated charcoal (i.e. Actisorb Plus,

© Woodhead Publishing Limited, 2011

Carboflex, Carbonet, Lyofoam C) and one did not contain activated charcoal but was highly absorbent (i.e. Release). A test solution containing two per cent diethylamine was applied to the dressings through a perforated plate at a rate of 30 ml/hour in an enclosed chamber which was connected via inlet and outlet ports to a portable ambient analyser (Miran 1B2, Quantitech). The volume of test solution which was applied to the dressings before 10 ppm of diethylamine was detected in the chamber was recorded. All dressings delayed the presence of diethylamine in the air above the dressings to some degree, including the Release dressing which did not contain activated charcoal. However, the presence of activated charcoal increased the amount of solution that could be added to the dressings compared with the absorbent dressing only. Dressings which had both activated charcoal as well as absorbent properties were the most effective in reducing the release of diethylamine into the surrounding air (i.e. Carboflex and Carbonet) (Thomas *et al*., 1998). The authors found that a combination of a moisture absorbent layer as well as an activated charcoal cloth layer greatly facilitated the reduction of the volatile compounds being released into the air.

Using a similar procedure as Thomas and colleagues, seven activated charcoal dressings (Carboflex, Lyofoam C, Carbonet, Sorbsan plus carbon, Actisorb silver 220, Carbopad VC, Clinisorb) and one absorbent dressing which had no activated charcoal (i.e. a standard Melolin dressing) were compared (Lee *et al*., 2007). The findings by Lee *et al*. were in agreement with those of Thomas *et al*., as they found that an activated charcoal dressing in conjunction with a fluid absorbent component to the dressing reduced the time for diethylamine to be detected in the surrounding air. Lee and colleagues also measured the air permeability and water vapour transmission of the test dressings. One product – Actisorb Silver – which did not contain an absorbent layer, was as effective in controlling the release of volatile compounds as two absorbent activated carbon products (i.e. Carbonet and Sorbsan with carbon).

Other absorbent materials/polymers

Cyclodextrins are cyclic oligosaccharides which are made up of six to eight glucopyranoside units attached by glucosidic bonds at C1 and C4. Cyclodextrins are capable of forming inclusion complexes with other molecules due to their toroidal shape which is largely hydrophobic. Malodours can be controlled through the use of cyclodextrins by incorporating fragrances as the inclusion molecules (to mask odour) or through absorption of odorous molecules into their internal structure (Buschmann *et al*., 2001). Lipman and van Bavel (2007) report an *in vitro* trial where a new cyclodextrin-incorporated hydrocolloid wound dressing reduced malodours likely to be emitted from wounds. Hydrocolloid dressings are self adhesive, absorbent, impermeable wound dressings which create a humid environment facilitating wound healing. They work by absorbing exudate fluid or by moisture forming a gel (Thomas, 1992). Hydrocolloid dressings do not act as odour absorbents, in fact, during absorption of the wound exudates in some types

© Woodhead Publishing Limited, 2011

of hydrocolloid, the 'semi-liquid' gels produced can emit an unpleasant odour (Thomas, 1992). Absorption of odorants by cyclodextrins is most effective in the presence of moisture, and as the hydrocolloid wound dressing creates a moist environment, the incorporation of the cyclodextrins with hydrocolloids enhance odour absorption by cyclodextrins. Incorporation of cyclodextrins into hydrocolloid wound dressings was effective in absorbing butyric acid and valeric acid odorants in an *in vitro* trial (Lipman and van Bavel, 2007). Odour absorption by the test cyclodextrin-hydrocolloid wound dressings was comparable with commercially available charcoal containing wound dressings (i.e. Actisorb, Carbonet, Carboflex). The presence of wound serum in the charcoal wound dressing may hinder odour absorption (Lipman and van Bavel, 2007); however, commercially produced odour absorbing hydrocolloid wound dressings are not yet available.

As well as cyclodextrins, other odour absorbent materials referred to for use in feminine hygiene products, disposable diapers, and incontinence products are zeolites, silicates, absorbing gelling materials, starches, ion exchange resins (e.g. Guarracino and Giovanni, 2000; Gagliardi *et al*., 2001). There is also some indication that alpha sepilolite, a natural clay mineral, may also be useful in reducing malodour and effective in wound management (Kose *et al*., 2005).

Disposable items for urinary and faecal incontinence typically perform better at retaining smell (as well as urine) than washable absorbent products made from rayon or polyester fibres. Disposable incontinence products are composed of either 'fluffed wood pulp fibres' or powdered superabsorbent polymers; the latter hold much more liquid for their weight than the wood pulp disposable materials do (Fader *et al*., 2008).

Natural fibres

Fabrics made from natural fibres, such as wool and cotton, have been found to exhibit lower odour after being worn next to the axillary region than do fabrics made from synthetic fibres such as polyester (McQueen *et al*., 2007). Wool in particular was perceived to have low-odour characteristics. As skin bacteria persisted longer in 100% wool fabrics than 100% polyester the authors concluded that absorption of odorous volatiles, rather than some inherent antimicrobial property, was likely to be the cause for the reduction (or lack of odour build-up) in the wool textiles (McQueen *et al*., 2007). In a later study, headspace axillary volatiles were measured via PTR-MS from previously worn wool, cotton and polyester fabrics (McQueen *et al*., 2008). Volatiles considered to be short-chain fatty acids, by-products from bacterial metabolism of axillary secretions, were found to be higher from polyester fabrics than cotton and wool. There was an increase in short-chain fatty acids over a seven-day period from polyester, but this was not observed for either wool or cotton fabrics. Textile products made from wool may have limited use in medical applications as they would not withstand rigorous cleaning and sterilisation procedures that other textiles such as cotton

© Woodhead Publishing Limited, 2011

and polyester can. Other protein fibres such as silk which have been treated with antimicrobial AEGIS AEM 5772/5 (alkoxysilane quaternary ammonium) treatments could be worn next to the skin to reduce symptoms of atopic dermatitis due to colonisation with *S. aureus* (Senti *et al*., 2006). Although these garments are not specifically used to reduce odour build-up, the silk fabrics may behave in a similar way as wool and have low odour intensity when worn.

17.4.3 Scented textiles

Application of fragrances to mask the presence of unpleasant odours is a common method employed to control odour within the home (e.g. air fresheners). Personal hygiene products and cosmetic items are frequently scented in order to mask natural odours emanating from the body. Most commonly, perfumed substances in the form of an aerosol, liquid or solid will be sprayed or rubbed directly onto the skin. Textiles and nonwoven fibrous hygiene products can also have scent applied. A challenge of incorporating fragrances into textiles is providing long-lasting scents. This is because, by nature, perfumes are volatile and the intensity of the fragrance will dissipate quickly. Encapsulating the liquid or gas fragrance in a small capsule for slow-release over time is the most common method for incorporating scent into textiles, whereby the storage life of the volatile compound can be extended for practical use.

Aromatherapy uses essential oils for therapeutic purposes and offers an alternative and more holistic approach to healing than traditional western medicine. Calming and relaxing or rejuvenating the body are possible benefits obtained from aromatherapy (Wheeler Robins, 1999). Therefore, in medical applications essential oils such as lavender may be used to enhance relaxation and help people sleep, with the additional benefit of masking malodours. Lennox (1997) reported that jasmine and lavender aromatherapy compounds have been used to mask the unpleasant odours in a nursing home. Incorporation of rosemary, lavender, jasmine, lemon and sandalwood on 100% cotton using an inclusion molecule in β-cyclodextrins, continued to emanate odour after 30 days following treatment (Wang and Chen, 2005). Their durability to laundering was not assessed. An alternative to using scent-encapsulated compounds on textiles is infusing scent molecules into polypropylene chips prior to melt spinning (Liu *et al*., 2009).

In some cases the masking effect may not be great enough to effectively eliminate extremely strong odours such as those emitted from infected malodorous wounds. A possible adverse effect is that the carer and patient could associate negative connotations with a once pleasant odour (Haughton and Young, 1995).

17.4.4 Refurbishment of textiles

The primary purpose of cleaning textiles is to remove soils and stains, but secondary to this is the removal of odours. In a healthcare facility, cleaning is

© Woodhead Publishing Limited, 2011

synonymous with sanitising and/or disinfecting as removal of potentially infectious microorganisms is paramount. Bedding linens, hospital supplied patients' and staff clothing are subjected to rigorous laundering, with special handling and washing requirements used to deal with linens and clothing which are known to be infected. High temperatures in wash and rinse liquid (65–80°C) as well as bleach-containing detergents or additional bleaching agents effectively kill bacteria in hospital laundries (Barrie, 1994). Therefore, a carry-over of odour on the reusable linens is unlikely. The combination of lower wash temperatures and non-bleach containing detergents results in bacteria surviving the laundering process and odour emanating from the clothing at a later time (Munk *et al*., 2001). In domestic laundering and drying situations, odour is not necessarily removed since certain strains of bacteria can survive the laundering process. If clothing is not quickly dried, odour can intensify as the remaining bacteria thrive in the moist environment, particularly on cellulosic fabrics (Nagoh *et al*., 2005; Munk *et al*., 2001). Munk *et al*. (2001) found that *P. aeruginosa* and *E. coli* Gram-negative bacteria were completely eradicated at 50°C wash temperatures; a wash temperature of 60°C was required to completely kill strains of *S. aureus* and *S. epidermidis*.

17.5 Future trends

Development and improvement of antimicrobials to be incorporated into textiles, not only to control potentially infectious microbes, but also to control or prevent the development of malodour, is ongoing. The textile industry is concerned with providing antimicrobials which are safe for the wearer/user of the textile, have a low environmental impact and yet are durable enough to be maintained throughout the lifetime of the textile. Absorption of odorants into the textile substrate is perhaps still the most effective means for preventing strong malodours being released from a textile. Research is likely to continue into the area of enhancing the effectiveness of odour absorbing compounds such as cyclodextrins within textiles; again, durability over the lifetime of the textile and safety to both user and environment being key issues.

With increased focus on developing effective odour-controlling textiles, improved methods for 'objectively' assessing an improvement or absence of odour is required. Due to the complexity and diversity of odorants which can emanate from the human body and infected wounds, and because of the variability in sensitivity of the sense of smell, the development of reliable and reproducible sensory test methods for detecting quality and/or intensity of odours retained within textiles is still needed. Attention should be given to the types of sensory methods used, the screening and selection of a sensory panel as well as appropriate methods for collecting odour on the textiles. Enhancement and refinement of the instrumental methods that can detect volatile odorous compounds in real time, to sensitivities closer to the odour thresholds, is still necessary in many applications.

© Woodhead Publishing Limited, 2011

17.6 Acknowledgement

The author would like to thank Mari Bergen for her advice and help in the preparation of this manuscript.

17.7 References

Altemeier W A (1938). The cause of the putrid odor of perforated appendicitis with peritonitis. *Ann Surg*, 107(4), 634–635.

American Association of Textile Chemists and Colorists (2004). *AATCC Test Method 100 Antibacterial Finishes on Textile Materials: Assessment of*. American Association of Textile Chemists and Colorists, Research Triangle Park, North Carolina.

American Society for Testing and Materials (2001). *ASTM E 2149-01: Standard Test Method for Determining the Antimicrobial Activity of Immobilized Antimicrobial Agents Under Dynamic Contact Conditions*. ASTM International, West Conshohocken, PA.

Amoore J E (1977). Specific anosmia and the concept of primary odors. *Chem Sense Flavor*, 2(3), 267–281.

Ara K, Hama M, Akiba S, Koike K, Okisaka K, *et al*. (2006). Foot odor due to microbial metabolism and its control. *Can J Microbiol*, 52(4), 357–364.

Bailey A, Pisanelli A M and Persaud K C (2008). Development of conducting polymer sensor arrays for wound monitoring. *Sens Actuators B*, 131(1), 5–9.

Baker P G and Haig, G (1981). Metronidazole in the treatment of chronic pressure sores and ulcers. A comparison with standard treatment in general practice. *Practitioner*, 225(1354), 569–573.

Barrie D (1994). Infection-control in practice – how hospital linen and laundry services are provided. *J Hosp Infect*, 27(3), 219–235.

Baydar A E, Petrzilka M and Schott M-P (1992). Perception of characteristic axillary odors. *Perfume Flavor* 17(6), 1–9.

Bird S and Gower D B (1982). Axillary 5-alpha-androst-16-en-3-one, cholesterol and squalene in men: Preliminary evidence for 5-alpha-androst-16-en-3-one being a product of bacterial action. *J Steroid Biochem Mol Biol*, 17(5), 517–522.

Borkow G and Gabbay J (2008). Biocidal textiles can help fight nosocomial infections. *Med Hypotheses*, 70(5), 990–994.

Boscaini E, van Ruth S, Biasioli F, Gasperi F and Mark T D (2003). Gas chromatography-olfactometry (GC-O) and proton transfer reaction-mass spectrometry (PTR-MS). Analysis of the flavor profile of grana padano, parmigiano reggiano, and grana trentino cheeses. *J Agric Food Chem*, 51(7), 1782–1790.

Bowler P G, Davies B J and Jones S A (1999). Microbial involvement in chronic wound malodour. *J Wound Care*, 8(5), 216–218.

Buschmann H J, Knittel D and Schollmeyer E (2001). New textile applications of cyclodextrins. *J Inclusion Phenom Macrocyclic Chem*, 40(3), 169–172.

Chambers E and Wolf M B (1996). *Sensory Test Methods*. American Society for Testing and Materials (ASTM), West Conshohocken, PA.

Chen K C S, Forsyth P S, Buchanan T M and Holmes K K (1979). Amine content of vaginal fluid from untreated and treated patients with nonspecific vaginitis. *J Clin Invest*, 63(5), 828–835.

Collier M (2000). Management of patients with fungating wounds. *Nurs Standard*, 15(11), 46, 48–50, 52.

© Woodhead Publishing Limited, 2011

Cook R L, Redondo-Lopez V, Schmitt C, Meriwether C and Sobel J D (1992). Clinical, microbiological, and biochemical factors in recurrent bacterial vaginosis. *J Clin Microbiol*, 30(4), 870–877.

Dankert J, Holloway Y, Bouma J, van der Werf J and Wolthers B G (1981). Metronidazole in smelly gynaecological tumours. *Lancet*, 318(8258), 1295.

Dravnieks A, Krotoszynski B K, Lieb W E and Jungermann E (1968). Influence of an antibacterial soap on various effluents from axillae. *J Soc Cosmetic Chem*, 19, 611–626.

Fader M, Cottenden A, Getliffe K, Gage H, Clarke-O'Neill S, *et al*. (2008). Absorbent products for urinary/faecal incontinence: a comparative evaluation of key product designs – Introduction. *Health Technol Assess*, 12(29).

Frank M, Ulmer H, Ruiz J, Visani P and Weimar U (2001). Complementary analytical measurements based upon gas chromatography-mass spectrometry, sensor system and human sensory panel: a case study dealing with packaging materials. *Anal Chim Acta*, 431(1), 11–29.

Gagliardi I, Guarracino M and Toro C (2001). U.S. Pat. 6,245,693. U.S. Patent and Trademark Office, Washington, DC.

Gao Y and Cranston R (2008). Recent advances in antimicrobial treatments of textiles. *Textile Res J*, 78(1), 60–72.

Greenwood J E (1997). Monitoring wound healing by odour. *J Wound Care*, 6(5), 219–221.

Grey J E, Enoch S and Harding K G (2006). Wound assessment. *BMJ*, 332, 285–288.

Guarracino M and Giovanni C (2000). U.S. Pat. 6,080,908. U.S. Patent and Trademark Office. Washington, DC.

Guillet G, Zampetti, A and Aballain-Colloc M (2000). Correlation between bacterial population and axillary and plantar bromidrosis. *Eur J Dermatol*, 10, 41–42.

Hampson J P (1996). The use of metronidazole in the treatment of malodorous wounds. *J Wound Care*, 5(9), 421–425.

Haughton W and Young T (1995). Common problems in wound care: malodorous wounds. *Br J Nurs*, 4(16), 959–963.

Henkin R I (1995). Body Odor. *JAMA*, 273(15), 1171–1172.

Holloway S, Bale S, Harding K, Robinson B and Ballard K (2002). Evaluating the effectiveness of a dressing for use in malodorous, exuding wounds. *Ostomy Wound Manage*, 48(5), 22–28.

Innes M E, Umraw N, Fish J S, Gomez M and Cartotto R C (2001). The use of silver coated dressings on donor site wounds: A prospective, controlled matched pair study. *Burns*, 27(6), 621–627.

International Organization for Standardization (ISO) (2007). ISO 20743: Textiles – Determination of antibacterial activity of antibacterial finished products. International Organization for Standardization, Genève.

International Organization for Standardization (ISO) (2008). ISO 5492: 2008 Sensory analysis – Vocabulary. International Organization for Standardization, Genève.

Jackson L (2001). Use of charcoal dressing with silver on MRSA-infected wound. *Br J Commun Nurs*, 6, S19–S26.

Jørgensen B, Gottrup F, Karlsmark T, Bech-Thomsen N and Sibbald R G (2008). Combined use of an ibuprofen-releasing foam dressing and silver dressing on infected leg ulcers. *J Wound Care*, 17(5), 210–214.

Jørgensen B, Price P, Andersen K E, Gottrup F, Bech-Thomsen N, *et al*. (2005). The silver-releasing foam dressing, Contreet Foam, promotes faster healing of critically colonised venous leg ulcers: a randomised, controlled trial. *Int Wound J*, 2(1), 64–73.

© Woodhead Publishing Limited, 2011

Jude E B, Apelqvist J, Spraul M and Martini J (2007). Prospective randomized controlled study of Hydrofiber (R). dressing containing ionic silver or calcium alginate dressings in non-ischaemic diabetic foot ulcers. *Diabet Med*, 24(3), 280–288.

Kalinski C, Schnepf M, Laboy D, Nusbaum J, McGrinder B, *et al*. (2005). Effectiveness of a topical formulation containing metronidazole for wound odor and exudate control. *Wounds*, 17(4), 84–90.

Kanda F, Yagi E, Fukuda M, Nakajima K, Ohta T and Nakata O (1990). Elucidation of chemical compounds responsible for foot malodour. *Br J Dermatol*, 122(6), 771–776.

Karlsmark T, Agerslev R H, Bendz S H, Larsen J R, Roed-Petersen J and Andersen K E (2003). Clinical performance of a new silver dressing, Contreet Foam, for chronic exuding venous leg ulcers. *J Wound Care*, 12(9), 351–4.

Kloos W E and Musselwhite M S (1975). Distribution and persistence of Staphylococcus and Micrococcus species and other aerobic bacteria on human skin. *Appl Microbiol*, 30(3), 381–395.

Kose A A, Karabagli Y, Kurkcuoglu M and Cetin C (2005). Alpha sepiolite: An old clay mineral a new dressing material. *Wounds: Compendium Clin Res Pract*, 17(5), 114–121.

Labows J N (1988). Odor detection, generation, and etiology in the axilla. In *Antiperspirants and Deodorants*, Laden K and Felger C B (eds.). Marcel Dekker, New York.

Labows J N and Preti G (1992). Human semiochemicals. In *Fragrance: The Psychology and Biology of Perfume*, Van Toller S D and Dodd G H (eds.). Elsevier Applied Sciences, London.

Lagro-Janssen T, Smits A and Van Weel C (1992). Urinary incontinence in women and the effects on their lives. *Scand J Prim Health Care*, 10(3), 211–216.

Lawless H T and Heymann H (1998). *Sensory Evaluation of Food: Principles and Practices*. Chapman and Hall, New York.

Lee G, Anand S C, Rajendran S and Walker I (2007). Efficacy of commercial dressings in managing malodorous wounds. *Br J Nurs*, 16(6), S14–S20.

Lennox M (1997). Aromatic mixer. *Elderly Care*, 9(1) 36.

Leyden J J, Kenneth M D, McGinley J, Holzle E, Labows J N and Kligman A M (1981). The microbiology of the human axilla and its relationship to axillary odor. *J Investig Dermatol*, 77(5), 413–416.

Lindinger W, Hansel A and Jordan A (1998). On-line monitoring of volatile organic compounds at pptv levels by means of proton-transfer-reaction mass spectrometry (PTR-MS). – Medical applications, food control and environmental research. *Int J Mass Spectrom*, 173(3), 191–241.

Lipman R D A and van Bavel D (2007). Odor absorbing hydrocolloid dressings for direct wound contact. *Wounds: Compendium Clin Res Pract*, 19(5), 138–146.

Liu Y, Fernando T and Pierce J D (2009). Consumer acceptability of scent-infused knitting scarves using functional melt-spun PP/PLA bicomponent fibers. *Textile Res J*, 79(6), 566–573.

Louhelainen K, Kangas J, Veijanen A and Viilos P (2001). Effect of in situ composting on reducing offensive odors and volatile organic compounds in swineries. *AIHAJ – Am Ind Hyg Assoc J*, 62(2), 159–167.

Mao J W and Murphy L (2001). Durable freshness for textiles. *AATCC Rev*, 1(11), 28–31.

Marshall J, Holland K T and Gribbon E M (1988). A comparative study of the cutaneous microflora of normal feet with low and high levels of odour. *J Appl Bacteriol*, 65(1), 61–68.

Marshall J, Leeming J P and Holland K T (1987). The cutaneous microbiology of normal human feet. *J Appl Bacteriol*, 62(2), 139–146.

© Woodhead Publishing Limited, 2011

McQueen R H, Keelan M and Kannayiram S (2010). Determination of antimicrobial efficacy for textile products against odor-causing bacteria. *AATCC Rev*, 10(4), 58–63.

McQueen R H, Laing R M, Brooks H J L and Niven B E (2007). Odor intensity in apparel fabrics and the link with bacterial populations. *Textile Res J*, 77(7), 449–456.

McQueen R H, Laing R M, Delahunty C M, Brooks H J L and Niven B E (2008). Retention of axillary odour on apparel fabrics. *J Textile Inst*, 99(6), 515–523.

Michaels J A, Campbell W B, King B M, MacIntyre J, Palfreyman S J, *et al*. (2009). A prospective randomised controlled trial and economic modelling of antimicrobial silver dressings versus non-adherent control dressings for venous leg ulcers: the VULCAN trial. *Health Technol Assess*, 13(56), 1.

Moody M (1998). Product focus. Metrotop: a topical antimicrobial agent for malodorous wounds. *Br J Nurs*, 7(5), 286.

Mooney E K, Lippitt C M, Friedman J and Plastic Surgery Educational Foundation Data Committee (2006). Silver dressings. *Plast Reconstr Surg*, 117(2), 666–669.

Morin R J and Tomaselli N L (2007). Interactive dressings and topical agents. *Clin Plast Surg*, 34(4), 643–658.

Munk S, Johansen C, Stahnke L H and Adler-Nissen J (2001). Microbial survival and odor in laundry. *J Surfact Deterg*, 4(4), 385–394.

Munk S, Munch P, Stahnke L, Adler-Nissen J and Schieberle P (2000). Primary odorants of laundry soiled with sweat/sebum: Influence of lipase on the odor profile. *J Surfact Deterg*, 3(4), 505–515.

Münter K C, Beele H, Russell L, Crespi A, Gröchenig E, *et al*. (2006). Effect of a sustained silver-releasing dressing on ulcers with delayed healing: the CONTOP study. *J Wound Care*, 15(5), 199–206.

Nagoh Y, Tobe S, Watanabe T and Mukaiyama T (2005). Analysis of odorants produced from indoor drying laundries and effect of enzyme for preventing malodor generation. *Tenside, Surfact, Deterg*, 42(1), 7–12.

Natsch A, Gfeller H, Gygax P, Schmid J and Acuma G (2003). A specific bacterial aminoacylase cleaves odorant precursors secreted in the human axilla. *J Biol Chem*, 278(8), 5718–5727.

Natsch A, Schmid J and Flachsmann F (2004). Identification of odoriferous sulfanylalkanols in human axilla secretions and their formation through cleavage of cysteine precursors by a C-S lyase isolated from axilla bacteria. *Chem Biodivers*, 1, 1058–1072.

Neuner-Jehle N and Etzweiler F (1991). The measuring of odors. In *Perfumes: Art, Science and Technology*, Muller P M and Lamparsky D (eds.). Elsevier Applied Science, New York.

Obendorf S K, Kim J O and Koniz R F (2007). Measurement of odor development due to bacterial action on antimicrobial polyester fabrics. *AATCC Rev*, 7(7), 35–40.

Ohge H, Furne J K, Springfield J, Ringwala S and Levitt M D (2005). Effectiveness of devices purported to reduce flatus odor. *Am J Gastroenterol*, 100(2), 397–400.

Pangborn R M (1984). Sensory techniques of food analysis. In *Food Analysis: Principles and Techniques*, Gruenwedel D W and Whitaker J R (eds.). Marcel Dekker, New York.

Parry A D, Chadwick P R, Simon D, Oppenheim B and McCollum C N (1995). Leg ulcer odour detection identifies beta-haemolytic streptococcal infection. *J Wound Care*, 4(9), 404–406.

Parsons D, Bowler P G, Myles V and Jones S (2005). Silver antimicrobial dressings in wound management: A comparison of antibacterial, physical, and chemical characteristics. *Wounds*, 17(8), 222–232.

Payne J D and Kudner D W (1996). A durable antiodor finish for cotton textiles. *Textile Chem Color*, 28(5), 28–30.

© Woodhead Publishing Limited, 2011

Persaud K C (2005). Medical applications of odor-sensing devices. *Low Extrem Wounds*, 4(1), 50–56.

Persaud K C, Khaffaf S M, Payne J S, Pisanelli A M, Lee D H and Byun H G (1996). Sensor array techniques for mimicking the mammalian olfactory system. *Sens Actuat B-Chem*, 36(1–3), 267–273.

Poteete V (1993). Case study: Eliminating odors from wounds. *Adv Skin Wound Care*, 6(4), 43–46.

Preti G, Cutler W B, Christensen C M, Lawley H, Huggins G R and Garcia C R (1987). Human axillary extracts: Analysis of compounds from samples which influence menstrual timing. *J Chem Ecol*, 13(4), 717–731.

Rennie P J, Gower D B and Holland K T (1991). In-vitro and in-vivo studies of human axillary odour and the cutaneous microflora. *Br J Dermatol*, 124(6), 596–602.

Rennie P J, Gower D B, Holland K T, Mallet A I and Watkins W J (1990). The skin microflora and the formation of human axillary odour. *Int J Cosmet Sci*, 12(5), 197–207.

Sato H, Morimatsu H, Kimura T, Moriyama Y, Yamashita T and Nakashima Y (2002). Analysis of malodorous substances of human faeces. *J Health Sci*, 48(2), 179–185.

Senol M and Fireman P (1999). Body odor in dermatologic diagnosis. *Cutis*, 63(2), 107–111.

Senti G, Steinmann L S, Fischer B, Kurmann P, Storni T, *et al*. (2006). Antimicrobial silk clothing in the treatment of atopic dermatitis proves comparable to topical corticosteroid treatment. *Dermatology*, 213, 228–233.

Shirasu M, Nagai S, Hayashi R, Ochiai A and Touhara K (2009). Dimethyl trisulfide as a characteristic odor associated with fungating cancer wounds. *Biosci Biotechnol Biochem*, 73(9), 2117–2120.

Spanel P and Smith D (1996). Selected ion flow tube: A technique for quantitative trace gas analysis of air and breath. *Med Biol Eng Comput*, 34(6), 409–419.

Stevens S S (1951). Mathematics, measurement and psychophysics. In *Handbook of Experimental Psychology*, Stevens, S. S (ed.). Wiley, New York.

Stone H and Sidel J L (2004). *Sensory Evaluation Practices*. Elsevier Academic Press, San Diego.

Stuetz R M, Fenner R A and Engin G (1999). Assessment of odours from sewage treatment works by an electronic nose, H2S analysis and olfactometry. *Water Res*, 33(2), 453–461.

Suarez F L, Springfield J and Levitt M D (1998). Identification of gases responsible for the odour of human flatus and evaluation of a device purported to reduce this odour. *Gut*, 43(1), 100–104.

Taylor D, Daulby A, Grimshaw S, James G, Mercer J and Vaziri S (2003). Characterization of the microflora of the human axilla. *Int J Cosmet Sci*, 25(3), 137–145.

Thomas S (1992). Hydrocolloids: A guide to the composition, properties and use of hydrocolloid dressings and the commercial presentations available. *J Wound Care*, 1(2), 27–30.

Thomas S, Fisher B, Fram P J and Waring M J (1998). Odour-absorbing dressings. *J Wound Care*, 7(5), 246–250.

Thomas S and McCubbin P (2003). An *in vitro* analysis of the antimicrobial properties of 10 silver-containing dressings. *J Wound Care*, 12(8), 305–308.

Tredget E E, Shankowsky H A, Groeneveld A and Burrell R (1998). A matched-pair, randomized study evaluating the efficacy and safety of Acticoat* silver-coated dressing for the treatment of burn wounds. *J Burn Care Res*, 19(6), 531–537.

© Woodhead Publishing Limited, 2011

Troccaz M C, Starkenmann C, Niclass Y, van de Waal M and Clark A J (2004). 3-Methyl-3-sulfanylhexan-1-ol as a major descriptor for the human axilla-sweat odour profile. *Chem Biodivers*, 1, 1022–1035.

Trumble W R and Stevenson A (eds.). (2002). *Shorter Oxford English Dictionary*, Oxford University Press, Oxford, UK.

van Toller S (1994). Invisible wounds: The effects of skin ulcer malodours. *J Wound Care*, 3(2), 103–105.

von Hartungen E, Wisthaler A, Mikoviny T, Jaksch D, Boscaini E, *et al*. (2004). Proton-transfer-reaction mass spectrometry (PTR-MS) of carboxylic acids determination of Henry's law constants and axillary odour investigations. *Int J Mass Spectrom*, 239, 243–248.

Wang C X and Chen S L (2005). Fragrance-release property of β-cyclodextrin inclusion compounds and their application in aromatherapy. *J Ind Textiles*, 34(3), 157–166.

Wheeler Robins J L (1999). The science and art of aromatherapy. *J Holistic Nurs*, 17(1), 5–17.

Williams K and Griffiths E (1999). Malodorous wounds: Causes and treatment. *Nurs Resident Care*, 1(5), 276–285.

Zeng X-N, Leyden J J, Lawley H J, Sawano K, Nohara I and Preti G (1991). Analysis of characteristic odors from human male axillae. *J Chem Ecol*, 17(7), 1469–1492.

Zlatkis A, Brazell R S and Poole C F (1981). The role of organic volatile profiles in clinical diagnosis. *Clin Chem*, 27(6), 789–797.

© Woodhead Publishing Limited, 2011

18

Textiles for medical filters

W. ZHONG, University of Manitoba, Canada

Abstract: Fibrous materials are suitable for applications involving filtration and separation because they have large surface areas and highly porous structures. Medical filters made from porous hollow fibers have important applications in providing long-term or temporary extracorporeal supports for failed human organs, such as the kidney, liver, lungs and pancreas. This chapter introduces the main types of polymers and structures for hollow fiber bioreactors, and applications of these bioreactors. The characterization and evaluation methods for these medical filters are also discussed.

Key words: filtration, hollow fiber bioreactors, hemodialysis.

18.1 Introduction

Textile or fibrous materials feature highly porous structures and large surface-to-volume ratios, and therefore meet such purposes as filtration and separation. Fibrous materials are versatile also because, termed 'biocompatible', they may fulfill the many biomedical end uses in, say, bioartificial kidneys, and liver and lung devices, i.e. uses based on the capacity of hollow fiber membranes for filtration and dialysis. These extracorporeal devices have been developed to perform critical functions in place of failing organs so as to improve, prolong, or save the life of a patient. The good news is that the design and development of such vital devices have long passed from hot topics into goals of strenuous efforts. This chapter is intended for a specification of what is worth knowing concerning this subject: the need and application of the various medical filters, how they come to work, and what must be done prior to and during the design and development (i.e. evaluation and characterization of their properties), followed with a short statement of what might be done about them in the future.

18.2 Key issues of medical filters

The regular life of a human being depends on the normal function of all his organs. Some of the organs are involved in the complicated processes of filtration of the waste, detoxification, metabolism, and transfer/exchange of mass/nutrients to/within the other parts of the body. Acute failure of any of these organs will lead to serious disturbance to the entire system of life, and is often fatal. Accordingly, extracorporeal devices and/or systems of devices have been developed either as substitutes for the failing organs or as means of temporary aid to patients one or several of whose organs are failing them.

© Woodhead Publishing Limited, 2011

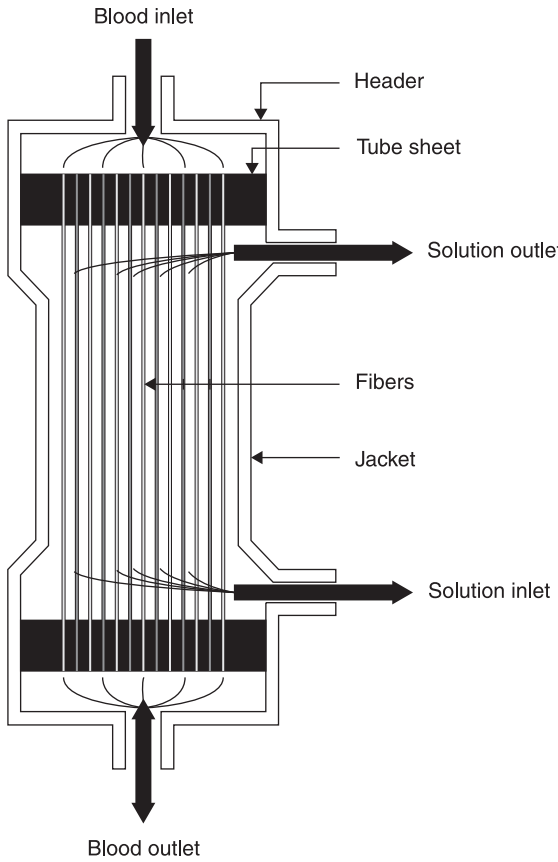
The hemodialyzer has been used clinically as an artificial renal support since 1923.[1] It provides two basic functions of a human kidney: hemodialysis and ultrafiltration. A hemodialyzer usually consists of two compartments divided by a semi-permeable membrane: one compartment is to contain blood from the patient, the other to be filled with a dialysate bath (i.e. water solution of electrolytes, the concentration of which should be such as to approximate levels normal for the human blood serum). The semi-permeable membrane between the two compartments will allow small molecules such as water and electrolytes to freely pass through, while red and white blood cells and fat and protein molecules will fail to pass through the membrane owing to their larger sizes, and be left behind in the blood compartment. Namely, only body waste will be filtered out from the human blood.

It can be seen that the semi-permeable filtering membrane or cellophane is the key element for the hemodialyzer. Early-stage hemodialyzers would contain cellophane tubing or stacked cellophane sheets,[1] and are nowadays looked upon with disfavor for their instability and poor efficiency. New, more efficient hemodialyzers are based on the function of hollow-fiber bioreactors (Fig. 18.1). A bioreactor consists of a large number of small fibers made from semi-permeable membranes, functioning collectively through a cylindrical shell/jacket.[1–3] The intratubular space of such a fiber is called the lumen or capillary space, and the space at the outside is called the extracapillary space. They constitute the two compartments across which filtration takes place.

Two types of polymers are exploited in building hollow fiber bioreactors: cellulose-based polymers and synthetic polymers.[4] Cellulose-based hollow fiber membranes are usually regenerated from cellulose. It is now clear that free hydroxyl groups (–OH) give poor blood compatibility,[5] and this explains why modified cellulosic materials have come to be used. Of the cellulose-based membranes, the most widely used are the cellulose acetate and cuprammonium rayon. Synthetic hollow fiber membranes can be made from polysulfone, polyamide and polyacrylonitrile. And modifications can be made to these materials to improve the function of a hollow fiber bioreactor.

Biocompatibility is the most important criterion for any polymer material to be used in direct contact with living organisms. In the case of hollow fiber bioreactors for hemodialysis, blood compatibility is essential because it helps avoid thrombus or blood coagulation. Also, since some of the small molecular weight toxins may become fast stuck to the albumin in the course of hemodialysis, making it difficult for them to be got rid of through diffusion, it is desirable that a hollow fiber bioreactor is anti-fouling, a property much dependent on the degree to which the device is good in terms of blood compatibility. To that end, a modification is made to hollow fiber bioreactors by using a novel material, polymers based on phospholipid, a substance plentifully found in the human cell membrane. 2-methacryloyloxyethyl phosphorylcholine (MPC) is a methacrylate monomer with a phospholipid polar group. Its copolymers have been used for the

© Woodhead Publishing Limited, 2011



18.1 A typical hollow fiber dialyzer.

modification of hollow fiber membranes. MPC polymers are used as an additive for polysulfone membranes, and have proved able to effectively reduce protein adsorption and platelet adhesion, improving blood compatibility as a result.[6,7] Cellulose acetate hollow fiber membranes are also modified with MPC polymers by means of blending or surface coating.[8,9] Membranes thus obtained manifest better permeability, hemocompatibility and cytocompatibility, and therefore can be used for the purpose of hemopurification and in the construction of liver assist bioreactors.

Polymers or monomers have also been used to modify the surfaces of hollow fiber membranes. Polyvinylpyrrolidone (PVP), a hydrophilic polymer, can be covalently conjugated with polysulfone membranes to improve their hydrophilicity. For the polysulfone membranes, this modification has been related to a much smaller number of adhering platelets and lower level of plasma protein adsorption as compared to those that have not undergone such modification.[10]

© Woodhead Publishing Limited, 2011

PVP can also be used as an additive to polyethersulfone membranes to improve their hydrophilicity and blood compatibility.[11,12] Poly(ethylene glycol) (PEG) is a hydrophilic polymer, very compatible with peptides and proteins, and nontoxic in the body. Polysulfone membranes with surface grafted PEG have been reported to have better hydrophilicity and blood compatibility.[13] Poly(acrylic acid) is believed to be able to improve surface performance of polysulfone membranes.[14] And there is evidence that single strand DNA immobilized onto polysulfone membranes with UV irradiation helps reduce protein adsorption onto, and increase blood compatibility of, the membranes.[15]

Use of physical methods (e.g. low-temperature plasma treatment) has been reported for the purpose of hydrophilic surface modification of polysulfone and polyacrylonitrile membranes.[13,16,17] For instance, treatment with water plasma and He plasma will drastically increase the surface hydrophilicity of polysulfone membranes and reduce their protein retention,[16] and the low-temperature water plasma treatment will result, as is believed, in permanent hydrophilic surface modification: the plasma treated polysulfone membranes remain wettable for over 16 months after the treatment.[17]

For the construction of membranes to be used in direct contact with living cells or tissues, special polymers or polymers with special structures as well as special treatments are needed. Various types of carbohydrate-immobilized phosphorylcholine (MPC) polymers can be used for both flat and hollow fiber membranes as interfaces with living cells, as is reported.[18] Cells adhering to the carbohydrate-immobilized MPC polymer surface function more efficiently as compared to cells adhering to the poly(*n*-butyl methacrylate) (PBMA) surface. The polymer is therefore believed to be able to provide a suitable surface for the cultivation of hepatocytes, manifesting its potential use in the construction of reliable bioartificial liver (BAL) devices. In the design of a cross hollow fiber bioreactor intended to support the long-term maintenance and differentiation of human hepatocytes, use is recommended of two types of hollow fiber membranes alternatively cross-assembled: one is the modified polyetheretherketone (PEEK-WC) that provides the cells with an oxygenated medium containing nutrients and metabolites, and the other is polyethersulfone that removed metabolites and cell specific products from cell compartment.[19] In this way, the two types of membranes mimic the *in vivo* arterious and venous blood vessels. According to the report, the human heptocytes will maintain the metabolic function for up to 18 days in such a system. In another design,[20] a multi-layer radial-flow bioreactor based on galactosylated chitosan nanofiber scaffold is made of 65 layers of stacked polycarbonate plates, onto which electrospun chitosan nanofibers will deposit to support the hepatocytes. These galactosylated chitosan nanofiber membranes will function more efficiently owing to improved cell adhesion. In addition, use of pig red blood cells in the culture medium is recommended because they provide oxygen for the hepatocytes. The result suggests that this type of bioreactor may provide short-term support for patients with hepatic failure.

© Woodhead Publishing Limited, 2011

18.3 Application of hollow fiber bioreactors

A well-known clinical application of hollow fiber bioreactors is in the hemodialyzer. Membranes used in clinical dialyzers are made from cellulose or synthetic polymers, and consist of bundles of about 10 000 hollow fibers the internal diameter of which is around 200 μm.[21] It allows blood to flow, a few ounces at a time, through the lumen of hollow fibers. Concentrations of the various electrolytes in the blood must be maintained within narrow limits if serious harm to the patient is to be avoided. To that end, the extracapillary space of the dialyzer is filled with the dialysate bath, a solution of some mineral, and its concentrations of sodium, potassium, chloride, and other electrolytes are made to approximate levels normal in the human blood serum. As a result, concentrations of these particles will in the course of dialysis become nearly equal on both sides of the membrane, and the undesirable waste products in the blood will be filtered out owing to the constant supply of fresh solution to keep levels of the waste low in the dialysate bath. The dialyzer is sometimes called the artificial kidney.

One more function of the artificial kidney is known as ultrafiltration, the removal of excess water from the body of the patient by the pressure difference between the lumen and extracapillary space. In the case where the patient has gained more than the recommended amount of fluid since the last dialysis, a negative pressure (suction) can be applied to the dialysate.

In the case described above, blood is taken from the artery of a patient by a system of tubes to the artificial kidney for dialysis and ultrafiltration, and will eventually be returned by one more tube to the patient's vein.[22] For a patient to undergo dialysis for 15 years, his blood will have to have contact with approximately 4000 m^2 of foreign surface, as is estimated.[23]

More recently, researchers in the field of tissue engineering have started to try to develop the so-called bioartificial (or bioengineered) artificial kidneys. They are supposed to perform, in addition to dialysis and ultrafiltration, more complicated tasks, termed as metabolic, endocrine, immune, and so on. Then bioartificial kidneys will play roles far beyond mere filtration, all in order to increase the chances of survival for patients with renal failure, acute or chronic.[24] These bioartificial kidneys are similar to a conventional hemodialyzer, except that viable cells are introduced to the extracapillary spaces and will then attach to the outer surfaces of hollow fibers. Alternatively, these cells can be entrapped in gels or immobilized onto polymeric microcarriers, thus prevented from blocking the pores or frustrating mass exchange across the membrane. These viable cells have been traced to such sources as human kidneys unsuitable for cadaver transplant and porcine kidney cells. After harvesting, culturing and seeding them onto the hollow fibrous bioreactors, they are expected to perform some of the metabolic functions on behalf of a kidney.[24,25]

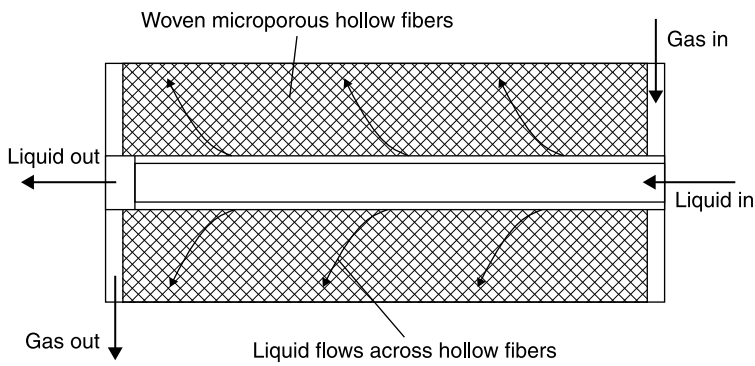
Similarly, hollow fiber-based bioartificial liver devices can be developed by culturing living hepatocytes (from animal or human) inside the hollow fibers and

© Woodhead Publishing Limited, 2011

causing blood of the patient to circulate in the extracapillary space. Toxic components in the blood that generally diffuse through the hollow fiber membrane into the luminal space are metabolized by the entrapped hepatocytes, and will then either diffuse back into the bloodstream or be washed out by way of the intraluminal stream. Such cells can be cultured outside the hollow fiber or, alternatively, the blood goes through the luminal space. It is crucial and challenging in the development of bioartificial liver devices to ensure that hepatocytes will function in such an *in vitro* environment.

Since similar polymer materials are generally used in the construction of bioartificial kidney and bioartificial liver, it is proposed that a well-designed hollow fiber filter system can be applied in an advanced total hemopurification system of bioartificial kidney and liver assist devices.[8,9] In such a system, blood taken from a patient suffering from both renal and hepatic failures is pumped into a plasmapheresis device to separate blood cells from plasma. Plasma thus separated enters a biohybrid liver assist reactor for detoxification. The detoxified plasma is then passed first through a hemofilter that performs the traditional function of hemofiltration, and then through a biohybrid renal tubule where reabsorption is carried out.

Hollow fiber bioreactors have also been applied in other extracorporeal devices, i.e. artificial lungs or extracorporeal blood oxygenators that serve as the cardiopulmonary bypass during open heart surgery. The hollow fiber membranes are used to separate blood from the gas. Blood flows outside and across bundles of hollow fibers while gas (usually oxygen or oxygen/nitrogen mixtures) flows inside the fibers. The diffusion of oxygen into and out of the bloodstream is driven by the concentration gradient across the membranes.[26–28] In addition to the hollow fiber modules similar to hemodialyzer, another structure for artificial lung is microporous woven tube (Fig. 18.2). A microporous woven fabric may be wound around a central tube to form a bundle.[29] Blood flow takes place across the woven fabric bundle while gas flows inside and oxygen diffuses in a way similar to that in a hollow fiber blood oxygenator.



18.2 Hollow fiber woven fabrics for an artificial lung.

© Woodhead Publishing Limited, 2011

Fiber bioreactors have been used in the development of bioartificial pancreas for treating diabetes.[30–33] Related research work is focused on the integration of islets of Langerhans into flat sheet or hollow fiber membranes. These membranes separate the cells from the blood and are permeable for glucose and insulin but impermeable to immunoglobulins and lymphocytes.[34] Most of the research in tissue engineered organs are carried out still in laboratories, however.

In addition to artificial organs, hollow fibers have a wide range of applications in the construction of enzyme reactors, and cell bioreactors for bacterial and yeast culture,[35,36] and even in waste treatment,[37,38] all because hollow fibers, as compared to flat membranes, provide larger surface areas and therefore better serve the purpose of mass transport and exchange between cultured cells and their environment.

18.4 Evaluation and characterization of medical filters

Various methods have been reported to characterize the structure of hollow fiber membranes (porosity, permeability, etc.) and what this structure is closely related to: mass transfer through the membranes in biomedical applications. Much of the work is intended to clarify how surface properties of materials influence their interactions with biological fluid (e.g. blood), cells and tissues.

18.4.1 Measurement of diffusion/hydraulic permeability of hollow fiber membranes

In contrast to flat membranes, hollow fiber membranes present considerable difficulties when efforts are made to measure their properties. For instance, for the purpose of measuring their permeability, special model-dialyzers may have to be designed and constructed. Such a model-dialyzer consists of only about one hundredth or even fewer fibers as compared to the real one. The advantages of the rarefied fiber model over a real dialyzer are: (i) All the hollow fibers can be ensured to be non-blocked and non-broken, (ii) interaction among the fibers can be negligible, and (iii) the flow field around the fibers can be visualized. As a result, transport properties of a hollow fiber membrane can be characterized quantitatively with higher accuracy.[39]

Or, measurement of a hollow fiber's diffusion permeability to small molecules can be conducted with a simple test setting: A bundle of hollow fibers is installed in a large bath containing a circulating saline solution (dialysate). Then the diffusive permeability of the membrane can be derived from the concentrations of the test fluid at the dialyzer inlet and outlet.[40] This process may lead, however, to filtration that occurs as a result of pressure during the supply of the test fluid. Accordingly, it is better not to use it for membranes with high hydraulic permeability (due to the pressure gradient). In summary, it is a low-precision method, which may not be suitable for solutes of high molecular weight as the difference between the dialyzer inlet and outlet is small.[41]

© Woodhead Publishing Limited, 2011

A method with higher precision involves the use of a solute, which is labeled with a radioactive isotope, as the test fluid. The test hollow fiber is dialyzed for a given period of time, and the residual solute is quantitate,[42] require special handling, however, and their quantities must be so restricted as to prevent overexposure. Thus its application is limited.[43]

Another technique involves use of optical fibers positioned at either end of the hollow fiber under test to allow continuous measurement of solute concentration in the fiber lumen. In the test, a laser light beam is emitted from one of these optic fibers into the test solution, then caught by the other optic fiber and detected with a silicon photodiode. The time-dependent delay in transmitted light intensity caused by the diffusion of solutes into the lumen is recorded for analysis to give concentration of the solute, and further the permeability. This method is independent of convective mass transport and osmotic flow through the membranes, which accounts for its superiority to ordinary techniques with respect to accuracy.[43,44]

Hydraulic permeability, or the filtration coefficient, can generally be derived from a filtration test when Dp=0, using this relationship:

$$J_V = k(\Delta P - \sigma\Delta\pi) \qquad [18.1]$$

where k is the hydraulic permeability or filtration coefficient, σ is the Staverman reflection coefficient, ΔP is the difference in solution pressure across the membrane, and $\Delta\pi$ is the difference in the osmotic pressure of the solution across the membrane.[41]

A parameter of clinical interest is the solute clearance that represents the rate of solute removed from the blood out of the incoming blood concentration (C_{blood}):[23]

$$\text{clearance} = \frac{\text{rate of solute removal}}{C_{\text{blood}}} \qquad [18.2]$$

18.4.2 Pore size and pore size distribution measurement

The characterization of pore size and pore size distribution for hollow fiber membranes can be achieved by either direct methods or indirect methods. Among the direct physical methods are the microscopic, bubble point, and mercury porosimetry. The indirect methods are based on the permeation and rejection performance of the membranes as related to reference molecules and particles,[45,46] including water permeation, gas permeation, solute transport, etc.

Microscopic observation and image processing of micrographs directly give visual information on membrane morphology such as surface pore shape and size, their distribution, etc, but will not provide any information of pore length or tortuosity. Available microscopic methods include transmission electron microscopy (TEM), scanning electron microscopy (SEM), field emission scanning electron (FESEM), and atomic force microscopy (AFM). In the use of both TEM

© Woodhead Publishing Limited, 2011

and SEM, a high electron beam energy is applied, causing damage to the surface of the sample and making observation difficult. In contrast, FESEM can be conducted at low beam energy, while AFM involves no electron beam energy at all. One more problem involved in the use of TEM and SEM is the complication in the preparation of samples. For one thing, the sample must be dried to avoid collapse of its original structure; then the dried membranes must be embedded and sliced, which are processes so intricate that deformation and deterioration may be caused to the sample. In contrast, since AFM is capable of images of the non-conducting surfaces in the air and even under liquids, samples need not to be dried for preparation and exposed to vacuum, and therefore are less likely to become damaged.[46] Accordingly, AFM is now the most popular technique for the microscopic observation of pore structures of membranes.[47–50] Still, the microscopic methods, including AFM, while they are capable of information on the structure of porous surfaces, they make no differentiation between open pores or dead-end pores. A way out is found in the combination of the various methods for a comprehensive description of the porous structure of hollow fiber membranes.[48]

Indirect testing methods are usually correlated with such permeation parameters as liquid flux, gas flux and solute flux, and are exploited to determine pore size for the pores open to flux. They give, therefore, only the minimal size of the pore constriction present along the whole pore. These methods are also used to characterize the bulk pore size of the membrane.

Relatively simple, the water permeability method is capable of indirect evaluation of pore sizes. The mean pore radius, r, can be calculated from:[51,52]

$$r = (8u\Delta x k\tau / A_s) \qquad [18.3]$$

where u is the viscosity of water, Δx the membrane thickness, τ the tortuosity defined by pore length/membrane thickness, A_s the membrane surface porosity, while $k = J/P$, J representing the water flux, and P the transmembrane pressure. In the constant pressure liquid displacement method (CPLM), this pressure is kept at a standard low value to avoid errors (permeability may vary with applied pressure).[53]

Measurement of the flow rate of a gas (usually pure nitrogen) through a porous membrane can also provide a mean to determine the mean pore radius of the membrane.[46,48] The permeation flux through the membrane is measured at different transmembrane pressures. From the linear plot of the permeability as a function of the mean pressure with intercept, B_0, and slope, K_0, the mean pore size can be calculated as:

$$r = \frac{16}{3}\left(\frac{B_0}{K_0}\right)\left(\frac{2RT}{\pi M}\right)^{1/2}\mu \qquad [18.4]$$

where R is the gas constant, T the absolute temperature, M the molecular weight of the gas, and μ the gas viscosity.

© Woodhead Publishing Limited, 2011

The solute permeation method is based on both filtration flux, J, and rejection rate, f, during the test. The rejection of a membrane to a solute of concentration, C_m, is defined as:

$$f = 1 - \frac{C_f}{C_m} \qquad [18.5]$$

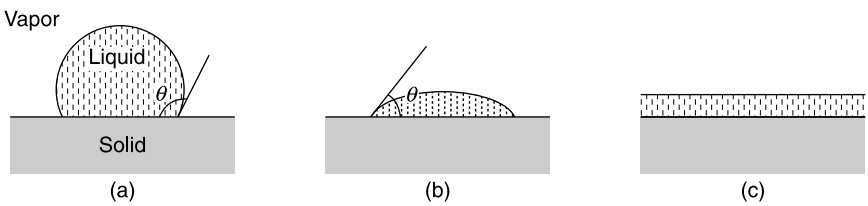
where C_f is the solute concentration after filtration. This parameter represents the membrane selectivity behavior to solute molecules. Several theories have been developed for the modeling of transport of solute molecules through membranes. And different expressions have been derived to give the relationship between pore size/structure and transport behaviors, as discussed in several reviews.[41,46,47]

The indirect methods for measuring porous structure of membranes provide only the average or mean values. For the clarification of relationship between transport behavior and pore structure, a method that is all-round and therefore likely to be well accepted, is still pending. Consequently, various characterization approaches are usually combined to give complementary information on the structure of a membrane.[45,48]

18.4.3 Evaluation of surface properties of medical filters

Surface properties of medical filters, such as cell adhesion and blood compatibility, are critical for their performance. Many methods have been contrived towards a clarification of these.

The measurement of the contact angle of a liquid (usually water) on a surface is one of the simplest approaches to the evaluation of the surface hydrophilicity of a membrane material.[13] By definition, a hydrophobic surface gives a contact angle larger than 90° while a hydrophilic surface renders the contact angle smaller than 90°, as shown in Fig. 18.3. When a liquid completely wets a hydrophilic surface, the contact angle turns zero (Fig. 18.3c). The commonest method of measuring the contact angle is to observe a sessile drop with a telescope or microscope. The contact angle is either determined directly with a goniometer, or the image is recorded by a video system and the contour is fitted by a computer using the Laplace equation.



18.3 Contact angle of a liquid on a horizontal surface: (a) Hydrophobic surface, (b) hydrophilic surface, (c) complete wetting of a surface.

© Woodhead Publishing Limited, 2011

For small drops where hydrostatic effects are negligible, the contact angle can be calculated from the height of the drop, h, and contact radius, a:[54]

$$\tan\left(\frac{\theta}{2}\right) = \frac{h}{a} \qquad [18.6]$$

For the measurement of the wettability of a membrane sample, the most sensitive and widely used method, or the Wilhelm method, functions as a result of the clarification of its interfacial adhesion tension by means of a recording electro-microbalance. The sample is suspended from one arm of the electro-balance and is partially submerged in a beaker of the test liquid. The platform holding the test liquid is mechanically moved in the vertical direction so that the dynamic contact angles can be measured.[6,55] Dynamic contact angles include the advancing contact angle (when the sample is submerged into the liquid) and the receding contact angle (when the sample is retrieved from the liquid).

Fourier transform infrared attenuated total reflection (FTIR-ATR) and X-ray photoelectron spectroscopy (XPS) are usually used to analyze surface chemistry of a membrane material. Special functional groups or chemical structures can be detected from these spectra.[13,16]

Protein adsorption onto the membranes can also be monitored. Model proteins used for this purpose are human plasma fibrinogen,[6] albumin, gamma-globulin,[7,14] etc. The amount of human plasma protein adsorbed on the polymer membrane can be determined by immersing for a certain period of time at 37°C a membrane into phosphate buffered saline (PBS) containing a plasma protein (like human plasma fibrinogen). The membrane is then gently taken out and rinsed several times with PBS. Next the membrane is transferred to a container with one per cent aqueous solution of sodium dodecyl sulfate (SDS) and shaken to remove the protein adsorbed on the surface. A protein analysis kit can be used to quantify the protein in the SDS solution.[6] A gold-colloid labeled immunoassay can be used to quantify protein adsorption from human plasma on the membranes, by following these procedures:[7] (i) Cut the sample membranes into disk-shaped bits and have them secured in a 24-well plate (ii) cause the membrane to contact first with PBS so as to equilibrate the surface and then with human platelet-poor plasma (PPP); (iii) have the plasma removed and the membrane washed with PBS; and (iv) make sure that the membrane is further incubated with one of the primary antibodies of albumin, γ-globulin and fibrinogen. The primary antibody that has reacted with the adsorbed protein is now fixed by cross-linking, and the secondary antibody is labeled with gold colloid. And number of the gold colloid particles can be quantified as a result of observation under a scanning electron microscope (SEM). The number of platelets adhering to the membrane can also be determined at the end of the following procedures:[7] (i) allow the human platelet-rich plasma (PRP) to contact the membrane samples; and (ii) wash the membranes and then put them into 1 wt% triton in PBS to lyse the adhering platelets. Adhering platelets can then be quantified by using the enzymatic method to clarify the lactic acid dehydrogenase activity of the lysate.

© Woodhead Publishing Limited, 2011

Cell adhesion to the membrane is critical for the survival and function of living cells on a bioengineered scaffold. Multiple researches have been performed to evaluate the adhesion and function of living cells on a bioreactor. For instance, it is now clear that human hepatocytes can be seeded in the extralumen space of the bioreactor, which is then perfused with oxygenated medium after the cells have adhered to the outer surface of the hollow fibers. Specimen of cell cultures can be observed by means of scanning electron microscopy. The morphological behavior of cells cultured in the bioreactor can be investigated by means of laser confocal scanning microscopy (LCSM) when the cells have become stained. Various stains can be used for the visualization of the different components of a cell.[18,19] The medium can be collected for the analysis of cell metabolite concentrations using high performance liquid chromatography (HPLC).[19]

18.5 Future trends

Medical filters made from porous hollow fibers have important applications in providing long-term or temporary extracorporeal supports for failed human organs, such as the kidney, liver, lungs and pancreas. Up to date, only the artificial kidney based on hollow fiber hemodialyzer has been clinically used. Bioengineered extracorporeal devices, which are based on functionalized hollow fiber membranes that support living cells, have been under extensive laboratory studies. Considerable challenges remain in the design and development of bioengineered devices that will manifest convincingly sufficient capacities before they are commercialized. One such challenge is how to provide the living cells with an *in vitro* environment that so closely stimulates the *in vivo* conditions in the healthy human organs that it will sufficiently fulfill the metabolic function necessary for the survival of a patient. As a result, bioengineered membranes will be the focus of investigation in the future because they are among the most likely material for the construction of assist systems that mimic functions of real human organs. In the course of making the related research and development efforts, the big issue is whether we can design and produce membrane materials that are biocompatible (including hemocompatible), able to support long-term cell growth and function, selectively permeable, and strong enough during their end uses. Modification of traditional materials by chemical conjugation or grafting, copolymerization, or physical blending are useful means of both promoting such material properties as cell adhesion and filtration or transfer efficiency and reducing the undesirable (e.g. protein adsorption). It is likely that related work will be intensified. In addition to efforts already made, new endeavors are envisioned: the development of animal models and clinical trials may be initiated or strengthened. Then it can be expected that some breakthrough will be made, all as a result of interdisciplinary efforts from scientists in material sciences, engineering, and medicine.

© Woodhead Publishing Limited, 2011

18.6 References

1 Clark W R (2000). Hemodialyzer membranes and configurations: A historical perspective. *Semin Dialysis*, 13(5), 309–311.
2 Tzanakakis E S *et al.* (2000). Extracorporeal tissue engineered liver-assist devices. *Annu Rev Biomed Eng*, 2, 607–632.
3 Sueoka A and Takakura K (1991). Hollow fiber membrane application for blood treatment. *Polym J*, 23(5), 561–571.
4 Woffindin C and Hoenich N A (1995). Hemodialyzer Performance – a Review of the Trends over the Past 2 Decades. *Artif Organ*, 19(11), 1113–1119.
5 Bowry S K (2002). Dialysis membranes today. *Int J Artif Organ*, 25(5), 447–460.
6 Ishihara K *et al.* (1999). Modification of polysulfone with phospholipid polymer for improvement of the blood compatibility. Part 1. Surface characterization. *Biomaterials*, 20(17), 1545–1551.
7 Ishihara K *et al.* (1999). Modification of polysulfone with phospholipid polymer for improvement of the blood compatibility. Part 2. Protein adsorption and platelet adhesion. *Biomaterials*, 20(17), 1553–1559.
8 Ye S H *et al.* (2006). High functional hollow fiber membrane modified with phospholipid polymers for a liver assist bioreactor. *Biomaterials*, 27(9), 1955–1962.
9 Ye S H *et al.* (2005). Design of functional hollow fiber membranes modified with phospholipid polymers for application in total hemopurification system. *Biomaterials*, 26(24), 5032–5041.
10 Higuchi A *et al.* (2002). Chemically modified polysulfone hollow fibers with vinylpyrrolidone having improved blood compatibility. *Biomaterials*, 23(13), 2659–2666.
11 Wang H T *et al.* (2009). Improvement of hydrophilicity and blood compatibility on polyethersulfone membrane by adding polyvinylpyrrolidone. *Fiber Polym*, 10(1), 1–5.
12 Torrestiana-Sanchez B, Ortiz-Basurto R I and Brito-De La Fuente E (1999). Effect of nonsolvents on properties of spinning solutions and polyethersulfone hollow fiber ultrafiltration membranes. *J Membr Sci*, 152(1), 19–28.
13 Song Y Q *et al.* (2000). Surface modification of polysulfone membranes by low-temperature plasma-graft poly(ethylene glycol) onto polysulfone membranes. *J Appl Polym Sci*, 78(5), 979–985.
14 Ulbricht M and Riedel M (1998). Ultrafiltration membrane surfaces with grafted polymer 'tentacles': preparation, characterization and application for covalent protein binding. *Biomaterials*, 19(14), 1229–1237.
15 Zhao C S *et al.* (2003). Surface characterization of polysulfone membranes modified by DNA immobilization. *J Membr Sci*, 214(2), 179–189.
16 Ulbricht M and Belfort G (1996). Surface modification of ultrafiltration membranes by low temperature plasma. 2. Graft polymerization onto polyacrylonitrile and polysulfone. *J Membr Sci*, 111(2), 193–215.
17 Steen M L *et al.* (2001). Low temperature plasma treatment of asymmetric polysulfone membranes for permanent hydrophilic surface modification. *J Membr Sci*, 188(1), 97–114.
18 Iwasaki Y *et al.* (2008). Interfacing biomembrane mimetic polymer surfaces with living cells – Surface modification for reliable bioartificial liver. *Appl Surf Sci*, 255(2), 523–528.
19 De Bartolo L *et al.* (2009). Human hepatocyte functions in a crossed hollow fiber membrane bioreactor. *Biomaterials*, 30(13), 2531–2543.

© Woodhead Publishing Limited, 2011

20 Chu X H *et al*. (2009). In vitro evaluation of a multi-layer radial-flow bioreactor based on galactosylated chitosan nanofiber scaffolds. *Biomaterials*, 30(27), 4533–4538.
21 Klein E, Ward R A and Lacey R E (1987). Membrane processes: dialysis and electrodialysis, in *Handbook of Separation Process Technology*, Rousseau R W (ed.). Wiley: New York, pp. 954–981.
22 Noordwijk J v (2001). *Dialysing for Life: The Development of the Artificial Kidney*. Kluwer Academic Publishers, Dordrecht; Boston, xii, p. 114.
23 Stamatialis D F *et al*. (2008). Medical applications of membranes: Drug delivery, artificial organs and tissue engineering. *J Membr Sci*, 308(1–2), 1–34.
24 Fissell W H *et al*. (2001). The role of a bioengineered artificial kidney in renal failure. *Bioartificial Organs Iii: Tissue Sourcing, Immunoisolation, and Clinical Trials*, 944, 284–295.
25 Saito A (2003). Development of bioartificial kidneys. *Nephrology*, 8, S10–S15.
26 Dierickx P W *et al*. (2001). Mass transfer characteristics of artificial lungs. *Asaio J*, 2001, 47(6), 628–633.
27 Dierickx P W, de Wachter D S and Verdonck P R (2001). Two-dimensional finite element model for oxygen transfer in cross-flow hollow fiber membrane artificial lungs. *Int J Artif Organ*, 24(9), 628–635.
28 Tatsumi E *et al*. (2000). Preprimed artificial lung for emergency use. *Artif Organ*, 24(2), 108–113.
29 Wickramasinghe S R, Garcia J D and Han B B (2002). Mass and momentum transfer in hollow fibre blood oxygenators. *J Membr Sci*, 208(1–2), 247–256.
30 Chae S Y, Kim S W and Bae Y H (2001). Bioactive polymers for biohybrid artificial pancreas. *J Drug Target*, 9(6), 473–484.
31 Morita S (1998). An experimental study on the bioartificial pancreas using polysulfone hollow fibers. *Jpn J Transplant*, 33(3), 169–180.
32 Boyd R F *et al*. (1998). Solute washout experiments for characterizing mass transport in hollow fiber immunoisolation membranes. *Ann Biomed Eng*, 26(4), 618–626.
33 Velez G M *et al*. (1997). Mass transfer in hollow fiber-type artificial pancreas devices. *FASEB J*, 11(3), 1676–1676.
34 Beck J *et al*. (2007). Islet encapsulation: Strategies to enhance islet cell functions. *Tissue Eng*, 13(3), 589–599.
35 Brotherton J D and Chau P C (1996). Modeling of axial-flow hollow fiber cell culture bioreactors. *Biotechnol Prog*, 12(5), 575–590.
36 Rios G M *et al*. (2004). Progress in enzymatic membrane reactors – a review. *J Membr Sci*, 242(1–2), 189–196.
37 Marrot B *et al*. (2004). Industrial wastewater treatment in a membrane bioreactor: A review. *Environ Prog*, 23(1), 59–68.
38 Visvanathan C, Ben Aim R and Parameshwaran K (2000). Membrane separation bioreactors for wastewater treatment. *Crit Rev Environ Sci Technol*, 30(1), 1–48.
39 Li M *et al*. (2002). An experimental investigation of hollow fiber flow in dialyzer. *Int J Nonlinear Sci Numerical Simulation*, 3(3–4), 261–265.
40 Klein, E *et al*. (1976). Transport and mechanical-properties of hemodialysis hollow fibers. *J Membr Sci*, 1(4), 371–396.
41 Sakai K (1994). Determination of Pore-Size and Pore-Size Distribution .2. Dialysis Membranes. *J Membr Sci*, 96(1–2), 91–130.
42 Sakai K *et al*. (1988). Determination of pore radius of hollow-fiber dialysis membranes using tritium-labeled water. *J Chem Eng Jpn*, 21(2), 207–210.

© Woodhead Publishing Limited, 2011

43 Kanamori T *et al*. (1994). An improvement on the method of determining the solute permeability of hollow-fiber dialysis membranes photometrically using optical fibers and comparison of the method with ordinary techniques. *J Membr Sci*, 88(2–3), 159–165.
44 Ohmura T *et al*. (1989). New method of determining the solute permeability of hollow-fiber dialysis membranes by means of laser lights traveling along optic fibers. *ASAIO Transact*, 35(3), 601–603.
45 Zhao C S, Zhou X S and Yue Y L (2000). Determination of pore size and pore size distribution on the surface of hollow-fiber filtration membranes: a review of methods. *Desalination*, 129(2), 107–123.
46 Nakao S (1994). Determination of Pore-Size and Pore-Size Distribution.3 Filtration Membranes. *J Membr Sci*, 96(1–2), 131–165.
47 Khayet M, Khulbe K C and Matsuura T (2004). Characterization of membranes for membrane distillation by atomic force microscopy and estimation of their water vapor transfer coefficients in vacuum membrane distillation process. *J Membr Sci*, 238(1–2), 199–211.
48 Khayet M and Matsuura T (2003). Determination of surface and bulk pore sizes of flat-sheet and hollow-fiber membranes by atomic force microscopy, gas permeation and solute transport methods. *Desalination*, 158(1–3), 57–64.
49 Hayama M, Kohori F and Sakai K (2002). AFM observation of small surface pores of hollow-fiber dialysis membrane using highly sharpened probe. *J Membr Sci*, 197(1–2), 243–249.
50 Feng C Y *et al*. (2001). Structural and performance study of microporous polyetherimide hollow fiber membranes made by solvent-spinning method. *J Membr Sci*, 189(2), 193–203.
51 Sakai K *et al*. (1987). Comparison of methods for characterizing microporous membranes for plasma separation. *J Membr Sci*, 32(1), 3–17.
52 Ishikiriyama K *et al*. (1995). Pore-size distribution measurements of poly(methyl methacrylate) hydrogel membranes for artificial-kidneys using differential scanning calorimetry. *J Colloid Interface Sci*, 173(2), 419–428.
53 Lee Y *et al*. (1997). Modified liquid displacement method for determination of pore size distribution in porous membranes. *J Membr Sci*, 130(1–2), 149–156.
54 Dimitrov A S *et al*. (1991). Contact-angle measurements with sessile drops and bubbles. *J Colloid Interface Sci*, 145(1), 279–282.
55 Lin Y C *et al*. (2009). Peptide modification of polyethersulfone surfaces to improve adipose-derived stem cell adhesion. *Acta Biomater*, 5(5), 1416–1424.

© Woodhead Publishing Limited, 2011

19

Textiles for patient heat preservation during operations

U. MÖHRING, D. SCHWABE and S. HANUS,
Textile Research Institute Thuringia-Vogtlande. V., Germany

Abstract: This chapter describes the problems of cold stress in patients during a long operation and the problems associated with it. The chapter further describes which types of textiles can be used to prevent hypothermia as a result of the patient's cold stress. Examples of these textiles are provided and predictions regarding future trends are given. The construction of textile-based heating systems is described, along with which types of textiles are used for different applications. The chapter compares the advantages and disadvantages of textile-based and non textile-based reusable and disposable heating systems.

Key words: spacer fabrics, heat preservation, warming systems, heating textiles, hypothermia.

19.1 Key issues and importance of preventing cold stress in patients during operations

Due to limited heat production, the body of a anesthetized patient loses a large amount of heat during an operation, resulting in hypothermia. Cold due to evaporation and flushing fluids brings down the patient's body temperature.[1] A number of potential complications are described in the medical literature,[2–5] including, among many other issues, the patient shivering due to cold, and an adverse reaction in the blood's coagulation factor. It is therefore important to maintain the patient's core temperature at between 35.5 and 37°C, both during the operation and afterwards, during the recovery phase in intensive care. Below 35°C hypothermia sets in.[1] Two types of patients are principally affected: children and elderly people. Children are not able to generate heat by amyostasia; furthermore, they have a large surface area in relation to their body weight. The reduced rate of metabolism in elderly people is a further factor leading to a higher risk of hypothermia. This effect will be increased by age-related diseases.[6] This, then, is the central problem. Current solutions involve different types of patient warming systems, based mainly on heated air or heating wires. These devices have a number of disadvantages: first, they are not sufficiently flexible, which means the system does not have an optimal fit with the body; second most of these systems impede the work of the surgeon due to their size; and, finally, they have limited breathability when plastic coated fabrics are used. Water convective systems have a further disadvantage, namely the risk of contamination with pathogenic microorganisms: when the recuperator is connected with the supply

© Woodhead Publishing Limited, 2011

tubes, an outlet for the water is inevitable. Microbiological investigations have shown that these units can be contaminated with viruses; this represents a high risk of infection.[7]

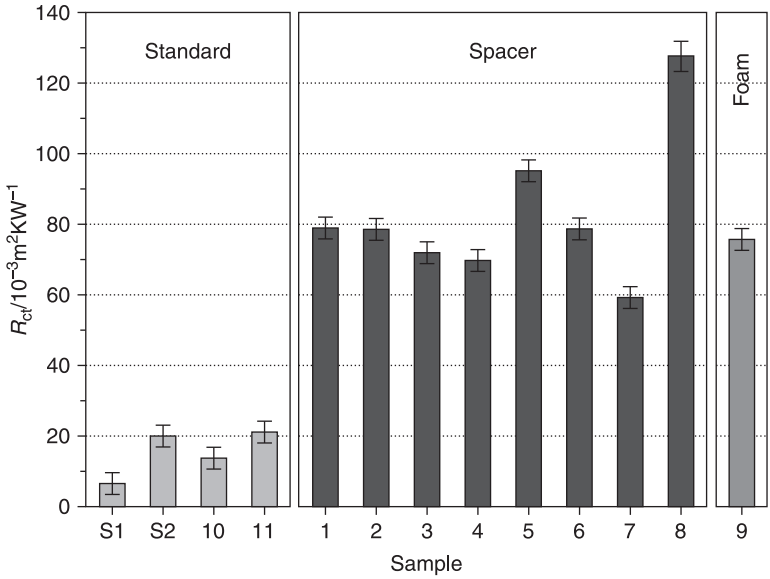
19.2 Main types of textiles used to maintain patient temperature during operations

A number of textile constructions can be used to improve and maintain the patient's temperature, in the form of covers for operating tables and undersheets. These include woven fabrics, laminated materials, three-dimensional knitted fabrics and also heat insulating nonwovens. Sufficient heat insulation is the essential factor in these constructions, as this is what allows the systems to work passively and prevent hypothermia. If constructed appropriately, knitted spacer fabrics have outstanding isolation ability and can decrease the risk of bedsores due to their pressure-reducing effect when used as undersheets. A system that combines these characteristics will be described below. This warming system basically consists of two components: an electronically controlled fan-assisted air heater and a textile multi-component layer. Heated air is conducted through the textile surfaces and escapes in the area close to the skin through a micro-filament woven fabric. Adaption for surgical requirements can be achieved by various product types. In a combined research project carried out by TITV Greiz and Hohenstein Institute, knitted spacer fabrics have been developed and investigated in order to determine their heat insulation properties. The project investigated how the structure of these fabrics needs to be constructed to prevent hypothermia in a patient during an operation. As reusable textiles, knitted spacer fabrics achieve a significant increase in heat insulation. If disposable materials are required, the use of nonwoven wadding is especially effective. The textile's surface should be structured to make sure that air can be embedded within. The heat insulation of the whole textile system could be raised by up to 36%.[8] Figure 19.1 compares the thermal resistance of standard materials, warp knitted spacer fabrics and foams.

19.3 Applications of textiles in maintaining patient temperature

To keep the patient's body at a sufficiently high temperature during an operation, different principles are implemented: textile passive systems, textile active systems, and convective and conductive systems that are based on non-textiles. The established systems currently on the market can be classified into two functional principles: heated air convection and heating by electrical conductive wires. The first of these are available as reusable products as well as disposable products. To ensure appropriate air circulation in these systems, the designs mostly call for a large area for air conduction. The result is that these systems need

© Woodhead Publishing Limited, 2011



19.1 Thermal resistance of spacer fabrics compared to standard- and foam-constructions. (Source: Hohenstein Institute)

a lot of space when they are placed on the patient. The delivery of heated air requires an external device and a tube connection. The device-related complexity is very high and the surgeons could be impeded by the tubes. Furthermore, the air cannot always be dispersed homogeneously across the whole covered area, because the air cools down within the chambers. Two further critical aspects must be taken into account with regard to systems constructed in this way: because the hot air current is in direct contact with the patient's skin, there is an increased need for fluid as a result of evaporation; secondly, because of air turbulence on and near the operation table hygienic concerns must also be considered just as critical.

The warming systems of the second category – those using electrically conductive wires – are always constructed as reusable products and consequently must be commercially reprocessable. Copper wires as well as carbon fibres are preferred for use as heating elements. The corrodibility of the copper wires requires an encapsulation by various types of synthetic films which decrease breathability. Furthermore, the systems are fairly inflexible and are limited in the extent to which they can be adapted to the patient's body.

Commonly used passive warming systems often fail to achieve the required level of heat preservation, especially when the operation involves larger orifices. They provide insulation against the environment and ensure that the body's heat is not lost. These covering materials which can be made, for example, of different fabric layers are often heated up in external devices for improved heat preservation.

© Woodhead Publishing Limited, 2011

Thin metal foils, which are also used, can reduce the loss of heat only for a limited time, for example in rescue or when newborns are transported within the operation room.[6]

19.4 Future trends

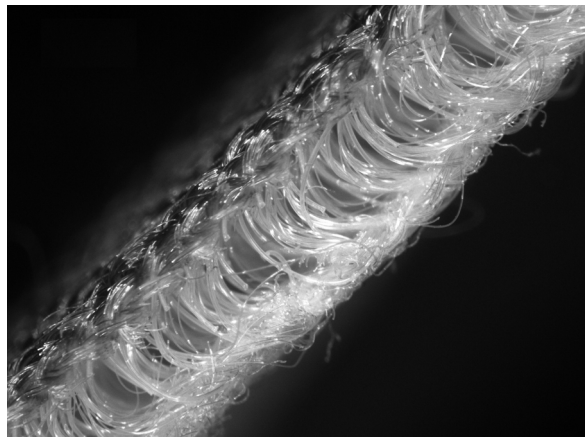
19.4.1 Increased use of textile-based systems (reusable vs. disposable)

Textile-based systems for surgical purposes are becoming increasingly important, with the trend towards an increased use of reusable instead of disposable materials a key factor. To compare the advantages and disadvantages of these materials, several different studies have been undertaken. One of these studies, called SAFEC (Safety/Ecology/Economy in the OR),[9] verifies that if the reprocessing is carried out professionally, and if a material- and quality-management is arranged, the requirements of reusable surgical textiles are completely fulfilled. Furthermore the study shows that reusable textiles have many positive properties, regarding the barrier effect, linting and mechanical stability under wet conditions, and go beyond the normative guidelines. Another study dealt with economic aspects, where significant differences could be determined. Concentrating solely on unit costs is deemed insufficient, because the cost benefit effect of alternative products is not considered. In particular, functional deficiencies would lead to an additional consumption of material and other unknown follow-up costs. Altogether the study comes to the conclusion that the additional costs for disposable products increase disproportionately the more dynamic and liquid-rich the surgeries become.[10]

19.4.2 Combination of heat and pressure reduction to prevent bedsores

Another trend is in the combination of heating and pressure reduction. Particularly in operations of long duration, local pressure strain in combination with moisture accumulation results in bedsores; these not only bring with them consequential costs but also an additional stress for the patient. Systems that include both functional principles can have many advantages in this case, and not only from an economic perspective. Three-dimensional structures have many advantages regarding the prevention of bedsores, as three dimensional knitted textiles in particular are able to provide not only air permeability but also moisture transport due to their mesh structure. The proven pressure-reducing properties of knitted spacer fabrics[11] may in this case be considered as a desirable additional feature. Figure 19.2 shows a warp knitted spacer fabric in cross section. The pile yarns can clearly be observed to maintain distance from the surface. These pile yarns work like thousands of small springs and are responsible for the pressure–elastic properties. As mentioned above, the porous structure enables high air permeability.

© Woodhead Publishing Limited, 2011



19.2 Cross section of a spacer fabric (source: TITV Greiz).

19.4.3 X-ray permeable systems using carbon fibres and other types of fibres

The use of active heating systems that are X-ray permeable constitutes another future direction. In this case, the use of electrically conductive non-metal fibres and the integration of these fibres into the textile fabric are particularly important. Compared to metallic fibres, non-metallic fibres such as carbon have advantages in terms of improved X-ray permeability. Indeed, X-ray permeable systems are offered on the market, but these systems are non-textile based and have limited air permeability and limited moisture conduction. Systems that are made exclusively of textile components can have outstanding advantages with regard to their clothing-physiological properties for this purpose.

19.4.4 Avoidance of 'open' systems: linting in the operation room

A further trend can be seen in attempts to decrease or avoid particle release (linting). Therefore the use of cotton textiles is already not recommended, as the amount of fluff particles is no longer acceptable in operating theatres today. Trilaminate and microfibres meet all demands regarding EN 13795.[12] With regard to the particle emission, 'open' heating systems are fraught with risk. As described above, there is a danger associated with swirling air and the related release of particles into the ambient air. In this respect, closed systems have clear advantages compared to 'open' systems and will be firmly established in the market in the future. Closed systems are characterized by the fact that the heating medium – water or air – cannot be released into the surrounding environment; it circulates in a closed cycle. Therefore, the possible disadvantages described above are mostly excluded.

© Woodhead Publishing Limited, 2011

19.4.5 The use of phase change materials

Phase change materials (PCMs) have become increasingly important in the last few years. These materials are storage media whose application in the field of textiles is based on physical principles. If the PCMs are heated and their melting point is reached, a phase change takes place where the solid state of aggregation changes into a liquid state of aggregation. During this phase transition heat quantities can be saved within the PCM. In the opposite case, the release of the saved heat quantities takes place during the transition from the liquid phase into the solid phase. For textile applications paraffin is the most frequently used raw material because it has the highest comparative heat capacities and the required temperatures can be adjusted in these materials. Different solutions are available for integration of the PCMs into textile structures. The application can be carried out using coating processes, but the PCM may also be applied directly onto the fibre. Thus, the PCM can be embedded permanently and the textile-specific properties like flexibility and breathability are preserved as far as possible. An example of this is the *smartcel*™*clima* fibre from Smartfiber AG.

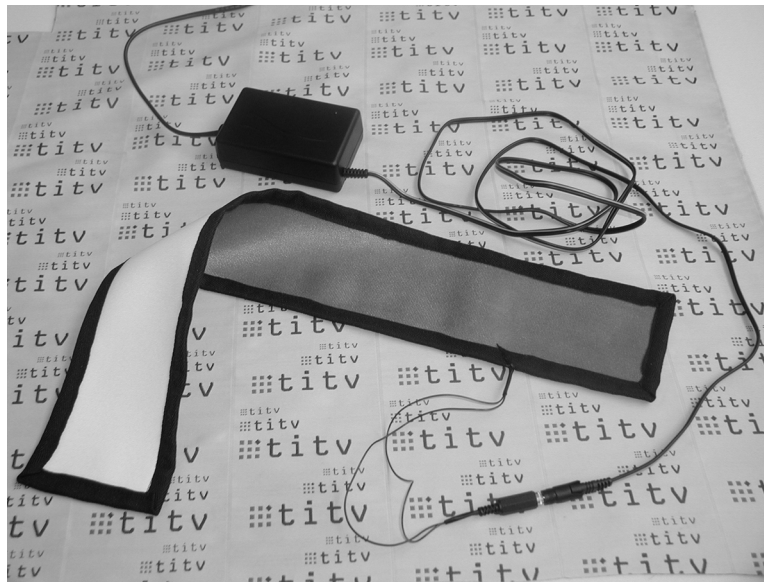
19.4.6 Outlook on thermal systems for physiotherapeutic applications

Textile-based active heating systems can not only be adapted for hypothermia prevention but also for physiotherapeutic use. In what is known as thermotherapy, the metabolism is stimulated and oxygen, nutrients, and antibodies are mobilized, with decay products also removed. The following effects mostly are attributed to the heat reaction in medicine: muscle relaxation, improvement of the blood flow, reduction in viscosity of the joint fluid, improvement of the extensibility of the connective tissue and pain relief.[13–15] Thermal therapy is applied, amongst other things, for muscular–skeletal diseases in the chronic state, for example when arthritis, spinal disorders and also muscular tension occur. Heating textiles can offer decisive advantages not only in thermal therapy, but also in wound healing,[16] offers a description of how the application of heat can help to reduce the wound infection rate when large interventions have been carried out, and can lead to a qualitatively improved wound healing process as measured by the increase of collagen.

Figure 19.3 shows how a prototype of a textile-based bandage could be shaped. This prototype delivers a heat output of app. 40 to 50 W at a low voltage sector of < 12 V. The advantages of such textile based systems are in their low weight and high flexibility as well as in their good air permeability. As these can be carefully shaped and applied to the human body, the areas that have to be medicated can be precisely heated. If metal-coated polymer yarns are used, no hot spots in the case of a local defect can occur, in contrast to solid metal heating wires.

Metal-coated polymer yarns are also used in the heatable underwear of the company WarmX, already commercially available, which was developed in

© Woodhead Publishing Limited, 2011



19.3 Textile-based bandage for electrical heating purposes (source: TITV Greiz).

cooperation with the TITV Greiz. Electrically conductive yarn materials with a silver coating are integrated directly into the textile (in this case a knitted fabric), ensuring that the area close to the skin is heated. The power is supplied by an electronically controlled rechargeable battery that can be removed from the textile. The heat output can be adjusted to several different levels. The textile is washable and has a very good wear comfort. Different designs mean that the system can be adapted to the individual needs of the wearer.

In summary, it can be said that both passive and active heatable textile structures display great deal of future potential and the possible applications are far from exhausted. Favourable clothing physiological characteristics, a high level of flexibility and low weight are only a few of the many advantages that make them destined for use in the field of medical textiles. The fact that the future trend is towards commercially repulpable multi-way products, presents a further incentive for textile materials to be established successfully in the market.

19.5 Sources of further information and advice

Publications

Schwabe D, Möhring U and Bartels V T (2005), 'Entwicklung von Textilien für OP-Abdecktücher und -Unterlagen', *Melliand-Textilberichte* 6, 444–446.

© Woodhead Publishing Limited, 2011

Rotsch C, Hanus S, Schwabe D, Oschatz H and Möhring U (2008), 'Lösungen für die Medizin aus der Textilforschung', *Orthopädie-Technik* 8, 634–638.
Schwabe D and Möhring U (2008), 'Mit 3D-Heizgewirken gegen das Auskühlen des Körpers während der Operation', *Kettenwirk-Praxis* 1, 23–24.
Schwabe D and Möhring U (2008), 'Beheizbare Abstandsgewirke', *Melliand-Textilberichte* 3–4, 84–85.

Websites

www.barkey.de
www.carbamed.ch
www.mi.med.uni-goettingen.de
www.moeckundmoeck.de
www.op-textilien.at
www.somamedical.de
www.titv-greiz.de

19.6 References

1 Hack M C M (05/2003). Zwischen Hypothermie und Hitzestress. *Geriatrie Praxis Österreich*, S. 15.
2 Lindahl S G E (1988). Energy expenditure and fluid and electrolyte requirements in anesthetized infants and children. *Anesthesiology*, 69(3), 377–382.
3 Grivel F, Herrmann C, Hoeft A and Candas V (1990). Skin temperatures and thermal judgments in sedentary subjects exposed to either heated floor or heated ceiling. International Conference on Environmental Ergonomics IV, October 1–5, 1990, Austin TX, pp. 40–41.
4 Frank S M, Fleisher L A, Breslow M J, Higgins M S, Olson K F, *et al*. (1997). Perioperative maintenance of normothermia reduces the incidence of morbid cardiac events–A randomized clinical trial. *J Am Med Assoc*, 277(14), 1127–1133.
5 Weyland W, Braun U and Kettler D (1997). *Perioperative Hypothermie*. Aktiv Druck and Verlag, Ebelsbach.
6 Durchdenwald G (2003). Hypothermie bei Patienten während und nach der Operation. *Pflegepraxis*, S.1 ff
7 Weitkemper H-H, Spilker A and Knobl H-J (3/2003). Untersuchung zur möglichen Keimreduzierung in Wasserkreisläufen am Beispiel von Hypothermiegeräten. *Kardiotechnik, Deutsche Gesellschaft für Kardiotechnik e.V*.
8 Bartels V T and Schwabe D (2004). Entwicklung von Textilien für OP-Abdecktücher und -Unterlagen zur Verbesserung und Aufrechterhaltung des Wärmehaushalts des Patienten. Schlussbericht zum Forschungsvorhaben AiF-Nr. 13368 BG/1, Bekleidungsphysiologisches Institut Hohenstein, Bönnigheim & Textilforschungsinstitut Thüringen-Vogtland, Greiz, 2004.
9 Feltgen M, Schmitt O and Werner H P (11/2000). Der Mensch im Mittelpunkt: OP-Abdeckmaterialien und OP-Mäntel sind Medizinprodukte. *Hygiene and Medizin*, 25(Suppl. 2), S. 60 ff.
10 Egger A (11/2007). Einweg versus Mehrweg. *Clinicum*, S. 44–45.

© Woodhead Publishing Limited, 2011

11 Heide M, Siegert D, Möhring U, Swerev M, Klein P, *et al*. (06/2002). Entwicklung funktioneller Abstandsgewirke als OP-Tischauflage. *Melliand-Textilberichte*, S. 441–442.
12 Egger A, Mittermayer H (11/2007). Mehrweg im Vorteil. *Clinicum*, S. 36.
13 Schmidt K L, Drexel H and Jochheim K A (1994). *Lehrbuch der Physikalischen Medizin und Rehabilitation*, S. 338.
14 Zenz M and Jurna I (2001). In: *Lehrbuch der Schmerztherapie*. Wissenschaftliche Verlagsgesellschaft.
15 Diener H C and Maier Ch (2008). In: Das Schmerztherapiebuch 2008. Urbanfischer, S. 393.
16 Coerper S (2/2002). Stimulation der Wundheilung durch Wärme: eine neue Behandlungsoption? *HARTMANN WundForum*, S. 16–18.

© Woodhead Publishing Limited, 2011

20

Evaluation of occupational clothing for surgeons: achieving comfort and avoiding physiological stress through suitable gowns

W. NOCKER, Consultant, Germany

Abstract: The basic demands to be fulfilled by surgical gowns are set forth in standard series EN 13795. However, no concrete data are given for comfort-related properties. Usually, people are physically and mentally fittest when they feel thermally well. In warm surroundings, this is only the case when the body can evaporate enough sweat. Studies have proven that the thermal comfort of a clothing system can be predicted when the ambient climate, the workload and the textile and physical parameters of the clothing layers are known. This chapter describes the factors that have to be considered when choosing textiles for use in the OR. Various test methods, standards and directives are mentioned which can assist in the evaluation of textiles. At present, the best thermal comfort achievable is reached by OR gowns consisting of microfibre fabrics. The high performance multiple use products made of three-layer laminates with different membranes cover a broad comfort spectrum, ranging from microfibre products to non-breathable coatings.

Key words: surgical gowns, physiological stress, thermophysiological comfort, water vapour resistance, OR protective clothing, EN 13795, ISO 11092, OR-textiles for burn injuries, physiological profile of demands.

20.1 Historical background

Up to the second half of the nineteenth century, surgeons wore dress suits, military physicians their uniforms. At that time, special textiles for the operating theatre, such as operating room (OR) gowns, gloves, face masks and caps were unknown. The patient's body was not covered during surgery. Wound infections were frequent. It was only at the end of the nineteenth century that special hospital garments, such as surgical gowns, were introduced. Patients now wore hospital shirts and were covered with fresh drapes during surgery (Colebrook and Hood, 1948).

Until the 1970s, OR textiles made from cotton or cotton blends were still common, although it was already known that they give off lints, causing a risk of infection (Hohenstein Report, 1992). Furthermore, it had already been pointed out that they are no barrier against microbiological penetration and permeation by liquids. After the European Directive (93/42 EWG 1993, 2007) came into effect, these textiles were no longer used in the direct vicinity of the operating area.

© Woodhead Publishing Limited, 2011

20.2 Surgical gowns

20.2.1 A medical product according to Standard EN 13795

Surgical gowns are medical products. As such, they have to fulfil the basic demands stipulated in the standard series (EN 13795, 2003, 2005, 2006). Their relevant properties, such as a barrier effect, purity, low particle release rates and strength are stipulated in EN 13795-1 (2003), the test methods in EN 13795-2 (2005) and the tolerances to be fulfilled for qualifying as a medical product in EN 13795-3 (2006). For various types of operations, different product qualities (performance classes) are defined as:

- *High performance*, for operations with a high risk of infection and penetration by liquids.
- *Standard perfomance*, for operations where these risks are lower.

The limit values apply both to disposable and reusable products. As soon as one of the required parameters is no longer being fulfilled, an OR gown must no longer be used as such.

20.2.2 Materials used for the two performance classes

Disposable surgical textiles for the standard performance class are mostly made from hydraulically entangled nonwovens with cellulose pulps and FC finish or from a spunbonded–meltblown–spunbonded construction made from PP fibres. Disposable surgical textiles for the high-performance class mostly consist of a spunbonded–meltblown–nonwoven construction with more weight per unit area or of film laminates made from hydraulically entangled nonwovens with a PE or PP film.

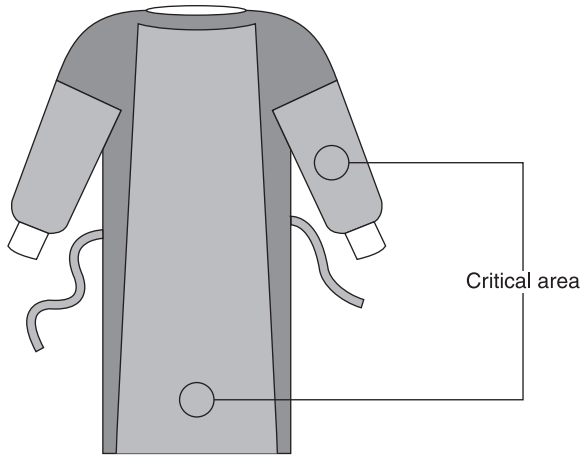
Reusable surgical textiles for the standard performance class are mostly made from PES filament woven fabrics with FC finish, whereas those for high performance are made of multi-layer laminates consisting of PTFE; PES or PU membranes. For details please see the following publications: Bärlocher and Gysin, 1994; Träubel *et al*., 1994; Bechter *et al*., 1995; Mehnert and Bernstein, 1996; Rigby and Subhash, 1996; Bernstein, 1997; Kunze, 1998).

As exposure and risks in areas close to the wound differ from those in more remote areas, the demands vary, too. Thus, the front side and the sleeves are ‘high-risk’ areas, whereas the remaining parts of a surgical gown are ‘low risk’ areas. Therefore, most OR gowns consist of different fabrics in different areas (Fig. 20.1).

20.3 Influences on wear properties

The protective clothing worn in an operating theatre must allow the wearer throughout work to (i) avoid thermo-physiological overload, and (ii) feel

© Woodhead Publishing Limited, 2011



20.1 Critical area.

comfortable in his or her clothing. This is essentially influenced by:

- The climate at the place of work
- The workload
- The entire clothing system
- The personal condition of the wearer.

20.3.1 Environmental climate

The climate in the operating room is mainly controlled by the installed air conditioning system. The technical details are governed by DIN 1946–4 (1986). The tasks to be fulfilled by the air conditioning system are as follows:

- Ensure the lowest possible degree of contamination, as the number of germs in the air is directly proportional to the post-operative risk of infection.
- Protect the instrument table.
- Ensure an adequate supply of fresh air and removal of noxious gases.
- Maintain positive pressure.
- Make the OR team feel thermally comfortable while being beneficial for the patient.

The room temperature in operating theatres – except for special rooms for treating burns – ranges from 22°C to 26°C. Air humidity is governed by DIN 1946-2 (1994). Absolute humidity should not exceed 11.5 g/kg of dry air, relative humidity should be not higher than 65%. This is the limit value at 22°C. For higher temperatures, the absolute value is the limit. At 26°C and 11.5 g/kg of dry air, the relative humidity is max. 54%. The minimum value for relative air humidity is 30%.

© Woodhead Publishing Limited, 2011

20.3.2 Workload

The metabolic turnover comprises basic turnover and performance-driven turnover and is a measure of how hard the work is. Depending on physical activity and body mass, the human body generates different amounts of heat. For a standard person (70 kg weight, 173 cm body height) the findings of Mecheels (1998) apply, as shown in Table 20.1. These values are higher for heavy persons and lower for lightweight persons.

During an operation, the surgeon and the assistants have to keep standing almost all the time, often for many hours. During work, the surgeon cannot lean on anything and often has to keep a slightly bent position. Only some operations can be done in a physically less strenuous sitting position, for example in eye surgery or neurosurgery. Every operation, however, requires a high degree of concentration and causes considerable psychical stress. A typical average value of a surgeon's metabolic turnover is 200 W (AIF Report No. 11090, 1999).

Table 20.1 Workload of a standard person during different activities

Activity	Workload (W)
Sleeping	85
Sitting	115
Standing	160
Light work	200
Medium work	280
Hard work	350
Very hard work	450

Source: Mecheels (1998, p. 18).

20.3.3 Clothing system

The typical clothing system worn by a person working in an operating theatre comprises:

- Private underwear and socks, mostly made of cotton or cotton blends, not sterile
- Hospital clothing provided by the hospital: long trousers, shirt with short sleeves (casaque), mostly made from a PES/CO blend; low-germ
- The sterile gown of performance class 'standard' or 'high'
- OR shoes, cap, face mask and gloves.

20.3.4 Personal condition of the wearer

The wearer's daily condition depends on numerous factors, such as sleep deficits, nutrition, consumption of coffee, tea, sweets, alcohol, medicine, and the like, physical fitness, psychical balance and motivation.

© Woodhead Publishing Limited, 2011

20.4 Elements of comfort

The elements of comfort comprise both ergonomic and physiological factors. *Ergonomic comfort* means how well the clothing fits, how much freedom of movement it affords and how easily the wearer can perform the necessary movements. It is easy to assess by trying the garment on. *Physiological comfort* is a combination of skin sensory comfort and thermo-physiological comfort.

Skin sensory comfort is influenced by a number of physical textile parameters which indicate how the fabric feels on the skin: soft, supple, hard, scratchy, sticky on humid skin, etc. For surgical gowns, skin-sensory comfort is important, especially in areas such as the sleeves where the gown is close to the skin and in direct mechanical contact with it. The skin sensory comfort grade, which summarises the mechanical contact perception, is determined by the following parameters: Sticking index, wetting index, surface index, number of contact points, stiffness. For details, see AIF Report No. 7169 (1988).

The human being is a homeothermal living organism and as such can only survive by keeping his body core temperature constant within narrow limits. It is only when heat production and heat dissipation are balanced and the body is in a neutral thermal state that a human being feels thermophysiologically comfortable. Otherwise, the body's heat content changes, and with it the body core temperature. The body's autonomous thermo-regulation system alone does not suffice. Therefore, clothing is needed to support the body in maintaining a comfortable heat balance.

Consequently, thermo-physiological comfort is mainly determined by the degree to which the clothing worn allows heat and moisture to permeate. When exposed to heat, the human body produces sweat and evaporates it on the skin in order to cool down and counteract hyperthermia. This is the body's most efficient mechanism to keep its core temperature as constant as possible.

Furthermore, thermo-regulation is influenced by the style and cut of the clothing. Between the fabric and the human skin, there are layers of air. They can either circulate within this space (=convection) or be exchanged (=ventilation). Convention and ventilation change when the wearer moves. The style and cut of a garment may either support or obstruct heat transmission and moisture transport.

20.5 Evaluation of parameters relevant for comfortable textiles

Depending on the wear situation, various comfort parameters of a textile can be determined. When there is no, or only slight, physical strain, insensible perspiration takes place (diffusion through the skin). The comfort parameters describing this phenomenon are heat transmission resistance, R_{ct}, moisture transmission resistance, R_{et}, and water vapour transmission index, i_{mt}. They are determined in a physiological textile laboratory using the skin model (sweating guarded hot plate) (ISO 11092, 1993).

© Woodhead Publishing Limited, 2011

During perceivable physical exertion, or in mild temperatures, human beings already feel that they sweat. This is sensible perspiration through perspiratory glands, but on the skin there is no liquid sweat yet. Evaporation takes place in the tubus or at the exit of the perspiratory gland. In addition to the parameters described above, this wear situation can be described by the buffer effect of the textile to perspiration in vaporous form (moisture balance value, F_d).

During heavy physical strain or in very hot climates, the human body sweats so heavily that sweat appears on the skin in liquid form. In addition to all the comfort parameters described above, this wear situation can be characterised by the buffer parameter, K_f, the liquid permeability, F_1, and the moisture quantity, G_2, collected. All these comfort parameters are described in detail in ISO 11092 (1993); BPI 1.2 (1963) and BPI 1.3 (1985).

As the exertion level during work is never constant, but marked by phases of higher or lower activities and breaks, the textile must have a sufficient heat insulation capacity when moist and should dry quickly to prevent post-exercise chill, so that the wearer does not cool off too much during breaks or after work. These characteristics are described by the heat insulation capacity of the moist textile R_{ct}, the drying time, t, and the water retention capacity, ΔG. All these parameters combined serve to calculate the thermo-physiological comfort grade. Extensive test series with human test subjects have proven the calculations to be correct (AIF Report No. 7169, 1988).

Based on the above-mentioned physical measurements, valid statements on the expected physiological comfort of textiles and on tolerances and limit values of such fabrics can be made. However, the expected physiological comfort not only depends on the properties of the material from which surgical clothing is made. The style and cut as well as all other parts of the clothing system also play an important part. The thermo-physiological comfort of the entire clothing system can be tested using a thermal mannequin with movable limbs as shown in Fig. 20.2.

Taking into account the calculated comfort parameters of all textiles, the physiological effect of the clothing system on the wearer, the comfort characteristics and the admissible applications in use can be predicted. The calculations are described in detail in AIF Report No. 7504, (1992).

20.6 Sweating as an effect of physiological stress

Human beings are constantly being exposed to stimuli from their environment. If these are perceived or considered as strenuous, they are called stressors. One can differentiate between social stressors (e.g. problems with colleagues), psychic stressors (e.g. time pressure, performance stress) and physical stressors (e.g. ambient temperature and humidity). They trigger physical reactions, such as changes in heart rate, blood pressure, increased secretion of perspiration, etc.

Surgeons and other people working in operating theatres are exposed to a wide variety of stressors. The ambient climate may increase the secretion of sweat, and

© Woodhead Publishing Limited, 2011

20.2 Thermal mannequin. Source: Hohensteiner Report (2000, p. 11).

additionally long or difficult operations cause mental stress. A sudden emotional shock (e.g. fright) may trigger an ergotropic reaction and profuse perspiration. As this happens independent of the skin's blood circulation, this phenomenon is also known as 'cold sweat'.

© Woodhead Publishing Limited, 2011

The following section will describe increased sweat secretion and the interaction with the clothing system. The *sensible sweat dissipation* through the eccrine perspiratory glands can be triggered by the following factors, as described by Randall (1946):

- Thermo-regulatory perspiration due to
  - stimulation of the skin's temperature sensors, or
  - rise of blood temperature.
- Physical perspiration due to
  - mental stress
  - emotional influences.
- Pharmacologically induced perspiration due to, for example,
  - nicotine
  - adrenaline
  - pilocarpine.
- Special reflectory perspiration due to
  - local pain
  - local pressure
  - spinal reflex
  - gustatory stimulus.

Regarding their secretion capacity, the eccrine perspiratory glands belong to the most productive glands of the entire human organism: They can produce up to (i) 2 litres of sweat per hour on the entire body surface when exposed to strong heat; and (ii) 10 litres of sweat per day when enough liquid is being drunk (Kuno, 1956).

Sensible dissipation of sweat through the apocrine perspiratory glands, which are mostly formed as appendices to hair follicles, occurs during emotional and sexual stimulation, and is sometimes also triggered by thermal stimuli (Fiedler, 1968). The apocrine perspiratory glands, also known as odour glands, are located only at certain parts of the body, such as the nose, the axillary, mamilla and genital regions.

In contrast to sensible perspiration, the insensible dissipation of sweat is an independent physical process in which diffusion takes place through the creatinine layer of the skin. According to Higuchi (1960) and Cros *et al*. (1961), it is essentially influenced by:

- The difference in partial water vapour pressure between the surface of the skin and the ambient air
- The water content of the stratum corneum
- Skin diseases.

The diffusion rates measured and described in literature range from 2 g/h (Kuno, 1956) to 24 g/h (Gasselt, 1965).

© Woodhead Publishing Limited, 2011

Usually it cannot be predicted how much thermoregulatory sweat will be produced during a certain activity. On the one hand, there are various types of human beings; some tend to sweat heavily, others not. On the other hand, body fitness and training condition make a difference. Above all, however, the physical textile characteristics of the clothing system worn play the most decisive part. In order to keep the body in the desired thermally neutral range, the heat dissipated must equal the heat produced. About ten per cent of the heat produced is given off through the air exhaled. Depending on the insulation capacity of the clothing system (heat transmission resistance, R_c) and the temperature gradient towards the environment, another part of the heat is dissipated in dry form, i.e. by conduction, convection and radiation. The rest must be carried away by evaporating sweat. This quantity is determined by the moisture transmission resistance, R_e, of the clothing system and the gradient between the partial pressure of the water vapour within the clothing system and the ambient atmosphere. If this heat quantity is smaller than the evaporative heat flow needed to maintain the heat balance, the skin temperature and the body core temperature will rise. The body reacts in that it perspires more heavily, although it cannot evaporate more sweat. Consequently, liquid sweat remains on the skin, or is absorbed by the underwear. This is where discomfort begins.

20.7 Controlled wear tests

The findings of the laboratory measurements (see Chapter 4) have to be checked by controlled wear tests with human test subjects in a climate-controlled chamber with monitored test measurements. This is necessary to find out whether the theoretically obtained results also apply in practice.

What is most important for successful tests is to select suitable and comparable test subjects. This is ensured by prior medical examinations assessing health condition and physical fitness. Only persons meeting the requirements qualify as test subjects. Here are some examples: Their perspiration intensity should be neither extremely strong nor extremely weak. As they need to subjectively describe how they feel they should be highly sensitive to feel even minor differences in heat perception, moisture perception, workloads and wear comfort. Once the test subjects have been selected, they have to be made familiar with the test conditions: When the actual tests begin, there should be no habituation effects falsifying the results. The tests should always be performed at the same time of the day in order to exclude time-related fluctuations. Never will so-called ‘quick and dirty tests’ with individual persons of unknown profiles lead to reliable results.

The objective parameters to be measured are, for example:

- Rectal temperature, T_{re}, as a measure of body core temperature
- Skin temperature, T_s, as an average of measurements on up to 10 different spots
- Heart rate, HR

© Woodhead Publishing Limited, 2011

- Temperature, T_M
- Relative humidity, F_M, in the microclimate, measured between the skin and the innermost textile layer.

This brings potentially disturbing variables under control and renders the tests in the climate-controlled chamber reproducible. In some cases, the work to be performed in the specific end use of the clothing cannot be done in a climate-controlled chamber. In this case, only the metabolic turnover can be simulated so that a work-specific factor is missing.

20.7.1 Results of wear tests with reusable and disposable gowns

Study 1

In its study AIF No. 11090 (1999) the Hohenstein Institute of Clothing Physiology tested 21 OR gowns on the articulated mannikin and 34 textile samples (with and without barrier effect) using the methods described in Section 20.5. The results served to work out a physiological profile of requirements to specify the wear comfort of OR gowns. It is based on water vapour transmission resistance, R_{et}, as determined by the skin model according to ISO 11092 (1993).

Table 20.2 shows a rating in grades ranging from 'very good' to 'unsatisfactory' which is assigned to the corresponding water vapour transmission rate, $R_{et,B}$, of the barrier textile and $R_{et,R}$ of the back textile and the physiological properties deducted thereof. The ratings in Table 20.2 serve to classify the barrier textiles tested as shown in Fig. 20.3. The water vapour transmission resistance $R_{et,R}$ of the back textiles ranged from 1.31 to 4.75 m^2 Pa/W.

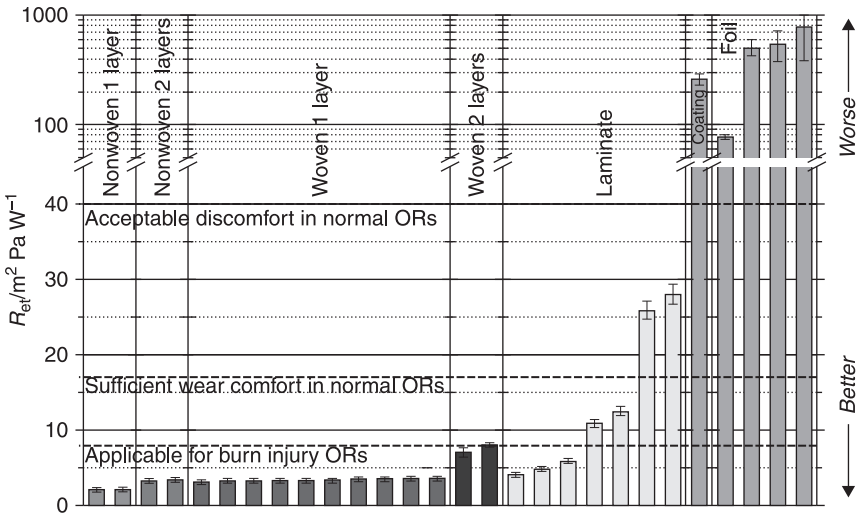
Four OR gowns were selected. The data obtained from measurements on the skin model and on the mannikin were fed into a prediction model (Mecheels and Umbach, 1976, 1977; AIF No. 7504, 1992). The metabolic turnover was assumed to be 200 W and an extended phase of discomfort was considered acceptable. In

Table 20.2 Physiological profile of demand for OR barrier and backside textiles, based on ISO 11092 measurements

Judgement	Required value (m^2 Pa/W)	Properties
Very good	$R_{et,B} \leq 8$	Suitable also in burn injury OR
Good	$8 < R_{et,B} < 17$	Sufficient wear comfort in a normal OR
Acceptable	$17 \leq R_{et,B} < 40$ or $R_{et,R} < 4$	Acceptable discomfort in a normal OR
Unsatisfactory	$R_{et,B} > 40$ and $R_{et,R} > 4$	Causes excessive heat strain

Source: Hohensteiner Report (2000, p. 12).
$R_{et,B}$ = water vapor resistance of barrier textile; $R_{et,R}$ = water vapour resistance of backside textile.

© Woodhead Publishing Limited, 2011



20.3 Classification of barrier textiles. Source: Hohensteiner Report (2000, p. 12).

this test setup, the thermal application range of the entire clothing system was calculated. For details, please see Table 20.3.

For the controlled wear tests, the ambient climate was selected to be 25°C, 50% RH, which is the upper temperature range according to DIN 1946, the metabolic turnover was 200 W. The test lasted for three hours.

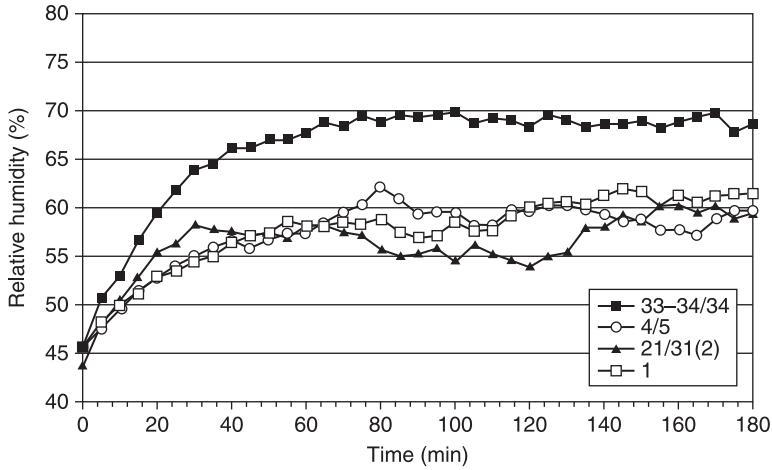
The rectal temperature, T_{re}, and the heart rate, HR, allow for a determination of the wearer's physical strain. At the end of the tests, all rectal temperatures were in the range of 37.15 ± 0.05°C and the heart rates were in the range of approximately 95 ± 5 /minute which means that the wearers did not suffer from physiological stress. Although the values had not reached a steady state at the end of the test, but still slightly rose, it is not to be expected that the discomfort zone would be reached, which begins at T_{re} = 37.5°C, even if the test took twice as long.

Table 20.3 Calculated 'range of utility', gown no. according AIF-report 11090

No.	Gown	Use	Performance	$R_{et,B}$ (m^2 Pa/W)	$R_{et,R}$ (m^2 Pa/W)	Range of utility (°C)
1	1	Disposable	High	5.89	5.89	15.9–32.8
2	4/5	Reusable	High	12.51	4.75	15.2–31.4
3	21/31	Reusable	Standard	3.28	3.82	17.0–33.8
4	33–34/34	Disposable	High	781	2.05	13.3–25.4

$R_{et,B}$ = water vapour resistance of barrier textile; $R_{et,R}$ = water vapour resistance of backside textile.

© Woodhead Publishing Limited, 2011



20.4 Relative humidities in a microclimate. Source: AIF No. 11090 (1999, p. 100).

Corresponding to the small differences in rectal temperatures, the average skin temperatures differed only to a minimum degree which are therefore considered to be insignificant. As expected, the average relative humidity in the microclimate showed significant differences between the OR gown with the impermeable barrier layer (no. 33–34/34) and the other samples. For more details, see Fig. 20.4. When relative humidity rises to 70%, the discomfort zone will be reached (Diebschlag, 1976). The wearers perceived this OR gown to be warmer, more humid and less comfortable than the other samples.

Study 2

Experience shows that the wear comfort of OR gowns made from microfibre fabrics is high. Often, a lower wear comfort is expected for multi-layer constructions. In another study (Hohenstein Test Report, 2000) 10 OR gowns made from three-layer laminates, microfibre fabrics and coated nonwovens were compared with each other. The task was to find out how comfortable three-layer products are to wear, compared to the other products. At first, the gowns and their materials were subjected to the tests described in Section 20.5. Subsequently, predictive calculations were performed to calculate the admissible thermal application range under conditions where the metabolic rate is 200 W and discomfort is acceptable for an extended period of time. The results are shown in Table 20.4.

Under typical conditions in OR theatres, with room temperatures between 22°C and 26°C (see Section 20.3.1), and at an assumed metabolic turnover of 200 W, merely slight losses of comfort can only be expected for the microfibre products

© Woodhead Publishing Limited, 2011

Table 20.4 Calculated 'range of utility' according the Hohenstein Test Report (2000)

No.	Gown	Use	Performance	$R_{et,B}$ (m^2 Pa/W)	$R_{et,R}$ (m^2 Pa/W)	Range of utility (°C)
1	MF 1	Reusable	Standard	2.66	2.68	14.0–26.8
2	MF 2	Reusable	Standard	3.68	3.68	13.9–26.4
3	MF 3	Reusable	Standard	4.21	2.13	14.0–26.6
4	3L, PTFE1	Reusable	High	12.27	2.13	13.6–25.2
5	3L, PTFE2	Reusable	High	2.60	2.14	14.1–27.0
6	3L, PU1	Reusable	High	44.80	44.80	12.3–20.9
7	3L, PU2	Reusable	High	15.69	1.17	13.1–24.1
8	3L, PTFE1	Reusable	High	2.97	2.97	14.1–26.9
9	PC 1	Disposable	High	∞	2.60	12.0–21.7
10	PC 2	Disposable	High	∞	2.51	12.0–19.3

MF = microfibre; 3L = three-layer laminate with PTFE membrane or PU membrane; PC = partial coating; $R_{et,B}$ = water vapour resistance of barrier textile; $R_{et,R}$ = water vapour resistance of backside textile.

and the laminates 5 and 8. For the other laminates, higher discomfort levels have to be expected; number 6 is already comparable to the uncomfortable impermeable products.

The admissible application range of the ten clothing systems tested excludes operating theatres for treating burns where the typical temperature is around 32°C. For the wearer this means that the longer he works the more probably he will suffer from rising discomfort and even hyperthermia due to his rising body core temperature. When the body core temperature exceeds 38.2°C, it is considered unacceptable to work on (Goldmann, 1988). The time until this point is reached is called 'tolerance time, t_{tol}'. When it is reached, the wearer should take a break. It is considered impossible to work when the body core temperature is higher than 38.5°C.

For use of the ten clothing ensembles in an operating theatre for treating burns, the body core temperature at the end of a three hours' surgery was calculated for a metabolic turnover of 200 W for a standard man. For all three microfibre products and for the three laminates with a PTFE membrane, T_{re} was < 37.6°C. This shows that these clothing systems are only slightly less comfortable than during use in a normal operating theatre. The second best class contains ensemble number 7 with PU-membrane: T_{re} = 37.8°C. The situation becomes worse for the ensembles number 6 (PU-membrane) and number 9 (partial coating). In them, core temperatures rise to 38.1 and 38.0°C. This is an intolerable discomfort, as liquid sweat is running down the wearer's entire body. The physiologically poorest ensemble appears to be number 10, which is mainly made of a non-breathable coated nonwoven. Final rectal temperature is T_{re} = 38.3°C. The critical value of 38.2°C is reached after t_{tol} = 121 min. Hence, this clothing system is not to be used in a burn injury OR.

© Woodhead Publishing Limited, 2011

At 25°C, the ten OR gowns were subjected to controlled wear tests. After 150 minutes, the objective and subjective data was evaluated (data from W.L. Gore). In the three microfibre products and in the laminates 5 and 8, the lowest body core temperatures were measured. In the two impermeable products the highest body core temperatures were measured. The relative humidities in the microclimate, measured in the chest area, were lowest (approx. 60% RH) for the microfibre products and for laminate number 8, the highest values (approx. 90% RH) were measured for the impermeable products and for laminate number 6.

The perceived moisture was assessed by grades and correlated ($r^2 = 0.78$) with the moistures measured:

- Grade 5 (= sweat flows at some areas) for the impermeables
- Grade 4 (= moist body, clothing sticks to the body) for laminate 6
- Grade 3 (= moist body) for all other products.

The heat perception correlates ($r^2 = 0.88$) with the body core temperatures:

- Grade 5 (= very hot) for the impermeables
- Grade 4 (= hot) for laminate 6
- Grade 3 (= very warm) for all other products.

The wear comfort had to be rated in grades ranging from grade 1 (= very good) to grade 6 (insufficient). The test subjects had not been given any criteria for this judgement. The results:

- Grade 4 (= sufficient) for the impermeable clothing system number 9
- Grade 3 (= satisfactory) for the impermeable clothing system 10 and for laminate 6
- Grade 2 (= good) for all others.

Based on the thermo-physiological data alone, a worse rating of the wear comfort could have been expected.

20.8 Purchasing criteria

20.8.1 Purchasing criteria for comfortable surgical gowns

The previous sections have shown that it is basically possible to predict the comfort properties of each OR gown for a certain application, independent of the performance level. From a garment physiological point of view, this would be desirable, even if cost constraints will rarely ever allow for this. However, the values for the water vapour transmission resistance of the barrier material and the back material recommended in Table 20.4 will assist in making the right decision and are accurate enough. After all, not all OR gowns are the same: style and design are different, and the ratio between barrier area and non-barrier area varies. Both studies have shown that the heat transmission resistance of the protective

© Woodhead Publishing Limited, 2011

textile is of minor importance. A change of this value has only a minimum effect on the total heat insulation system of the entire clothing system. What is decisive are the layers of clothing and air underneath the OR gown. Therefore, it is not a must to specify a value for the heat transmission resistance to be fulfilled by a comfortable OR gown.

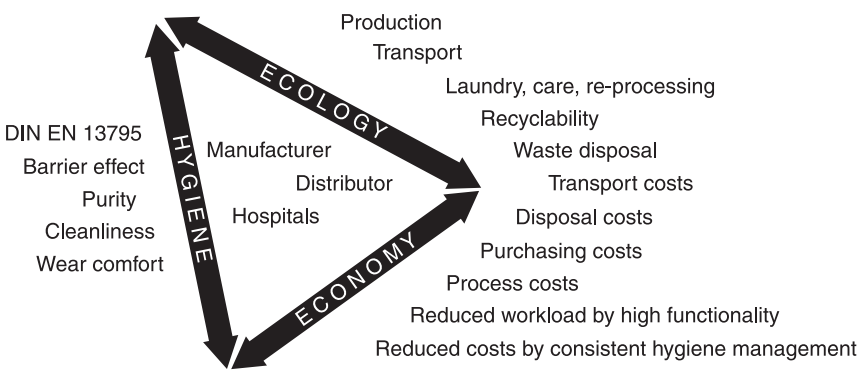
It is physiologically advantageous if the garment has a low weight. The heavier it is, the more strenuous it will be to wear: the metabolic turnover will rise (Dorman *et al*., 2005). Most disposable products have a clearly lower weight per unit area than reusable products. All the same, this parameter should not be considered too important, as the weight of the OR gown is only a minor percentage of the weight of the entire clothing system (see Section 20.3.3).

20.8.2 Purchasing criteria for disposable and reusable surgical gowns

The procurement of OR gowns is a complex decision process. The most important criterion is to fulfil the hygienic demands set forth in EN 13795. Wear comfort is of minor importance; economical and ecological criteria have to be considered first (Fig. 20.5).

From 2003 to 2009, the Technical University of Dresden conducted an interdisciplinary cross-divisional project to 'evaluate OR textiles according to hygienic, ecological and economical aspects'. In the following, some results of the 'Summary of the Research Results' (Cherif *et al*., 2009) will be described.

Three hundred and fifty-four hospitals reported the actual situation in their supply with OR textiles. The four most important criteria specified in their purchase inquiries and bids are: supply safety, reliability, cleaning quality, purchase price. 54% of the respondents use only disposable OR gowns, 26% use both disposable and reusable gowns, and 20% use only reusable gowns. The most



20.5 Polarity of criteria to assess the performance of surgical textiles. Source: Cherif *et al.* (2009, p. 6).

© Woodhead Publishing Limited, 2011

important reasons for using disposable OR gowns are safety and ease of use. The most important reasons for reusable OR gowns are wear comfort and ecological aspects. For the supply chain managers of reusable OR gowns it is decisive that the functional properties are preserved for as many cycles of use as possible. The field study of the interdisciplinary project included three groups of high performance reusable OR gowns which had been tested throughout 70 cycles of use: PES filament wovens with a silicone coating, three-layer laminates with a PU-membrane, and three-layer laminates with a PTFE-membrane. 'It was proven that reusable textiles are commercially available which are already very close to the technological optimum and which have a long service life of at least 70 cycles of use.' (Cherif *et al*., 2009, p.74). Regarding wear comfort, the reusable OR gowns with a PTFE membrane obtained the best results, and were graded as 'good'. Their wear comfort was higher than that of the disposable gowns.

20.9 Conclusions and recommendations

When feeling thermally comfortable, the body's heat balance is in order. This is important because the efficiency of a human being is usually highest when he, or she, feels thermally well. As described in Section 20.6.1, the maximum heat quantities which can be conducted off in dry and in moist form depend on the gradient between temperature and partial pressure combined with heat and moisture transmission resistance. In the climatic conditions of a normal operating room, about 40% of the metabolic turnover can be conducted away in dry form, whereas in a burn OR this value sinks to 20%. Low relative humidities in the microclimate next to the skin are advisable, as they increase thermal well-being: At the same ambient temperature, a climate is perceived to become hotter as the higher relative humidity increases (Schmidtke, 1974). Therefore, for people working in operating theatres the heat dissipated by evaporated sweat is decisive for how thermally comfortable they feel.

The measuring methods and calculations described in Section 20.5 basically predict the wear comfort of a clothing system for a given application with sufficient precision. When it comes to judging the comfort properties of an OR gown alone, the water vapour transmission resistance of the barrier and the back textile is a practical and sufficiently precise criterion to determine the thermophysiological comfort to be expected. Certified test institutes are in a position to perform these measurements according to ISO 11092. The recommendations given in Table 20.2 should become part of the normative section of EN 13795–1. The information currently given in Annex A are not relevant for comfort. The OR gowns cover the entire range from 'very comfortable' to 'intolerable' regarding their comfort properties. Microfibre products afford the highest comfort, whereas the OR gowns mainly made from non-breathable coated nonwovens are of utmost discomfort. They must not be used in burn ORs and even in normal ORs they are only of very limited applicability. In between these two

© Woodhead Publishing Limited, 2011

groups there are the three-layer laminates with different types of membranes. Their water vapour transmission resistance ranges from 'very low' to 'very high'. Some products reach a wear comfort which equals those of the microfibre products. Since all layers of a clothing system contribute to the wear comfort, however, it is advisable to improve not only the protective layer, but also the other parts of the clothing.

In order to raise the acceptance of reusable OR gowns, a high number of use cycles is necessary. Even if the interdisciplinary scientific study has shown good results for the high performance reusable gowns, details of the investigations show that there is still enough potential to improve the number of reprocessing cycles attainable.

20.10 References

93/42 EWG (1993, 2007). Richtlinie über Medizinprodukte.

AIF-Nr. 7169 (1988). Schlussbericht zum Forschungsvorhaben *Quantifizierung, Messung und Bewertung des hautsensorischen Tragekomforts von Textilien durch ein Vorhersagemodell*, Bekleidungsphysiologisches Institut Hohenstein, Bönnigheim.

AIF-Nr. 7504 (1992). Schlussbericht zum Forschungsvorhaben *Grundsatzuntersuchung über die prozessgesteuerte Simulation der Thermoregulation des Menschen*, Bekleidungsphysiologisches Institut Hohenstein, Bönnigheim.

AIF-Nr. 11090 (1999). Schlussbericht zum Forschungsvorhaben *Erforschung der bekleidungsphysiologischen Anforderungsprofile an Textilien für Krankenhaus-Schutzbekleidung*, Bekleidungsphysiologisches Institut Hohenstein, Bönnigheim.

Bärlocher K and Gysin H P (1994). Vorbehandlung und Veredlung von Textilien aus Zellulosefasern, *Textilveredlung*, 29(1/2), 18–25.

Bechter D, Barthau R and Herlinger H (1995). Polymer-Faser-Haftungen bei Beschichtungen – 2.Mitteilung:Einfluß der Porosität auf die Haftung mikroporöser PUR-Beschichtungen, *Melliand Textilberichte*, 76(4), 263–265.

Bernstein U (1997). Microfasertextilien für Schutzkleidung mit Barriereeigenschaften (BMWI-Projekt 190/93), *Technische Textilien/Technical Textiles*, 40(2), 105.

BPI 1.2 (1993). Standard-Prüfvorschrift *Bestimmung der Pufferwirkung von Textilien mit dem Thermoregulationsmodell der menschlichen Haut*, Bekleidungsphysiologisches Institut Hohenstein, Bönnigheim.

BPI 1.3 (1985). Standard-Prüfvorschrift *Bestimmung der Wärmeisolation eines feuchten Textils mit dem Thermoregulationsmodell der menschlichen Haut*, Bekleidungsphysiologisches Institut Hohenstein, Bönnigheim.

Cherif Ch, Günther E, Jatzwauk L and Mecheels S (2009). *Evaluierung von OP-Textilien, Ergebnisse einer Untersuchung nach hygienischen, ökonomischen und ökologischen Gesichtspunkten*, TU-Dresden.

Colebrook L and Hood A M (1948). Infection through soaked dressings, *Lancet*, 252, 6531, 682–683.

Cros J, Klotz H P and Tremolières J (1961). *Ann d'Endocrinol*, 22, 939.

Diebschlag W (1976). *Thermophysiologische Untersuchungen am Menschen als Grundlage einer optimalen Auslegung von Bekleidungssystemen*, Habilitationsschrift, TU-München.

DIN 1946 – 2 (1994). Raumlufttechnik : *Gesundheitstechnische Anforderungen*.

© Woodhead Publishing Limited, 2011

DIN 1946 – 4 (1999). Raumlufttechnik: *Raumlufttechnische Anlagen in Krankenhäusern*.
Dorman L, Havenith G and Thermprotect network (2005). *The Effects of Protective Clothing on Metabolic Rate*, ICEE congress, Ystad, Sweden.
EN 13795, Surgical drapes, gowns and clean air suits, used as medical devices, for patients, clinical staff and equipment. part 1 (2003): *General requirements for manufactures, processors and products*. part 2 (2005): *Test methods*. part 3 (2006)*: Performance requirements and performance levels*.
Fiedler H P (1968). *Der Schweiß*, Aulendorf, Editio Cantor.
Gasselt H R M van and Vierhout R R (1963). *Dermatologie*, 127, 255.
Goldman R (1988). Standards for human exposure to heat. In: *Environmental Ergonomics*. Taylor and Francis, London, pp. 99–136.
Higuchi P (1960). *Soc Cosmet Chem*, 11, 85.
Hohensteiner Report (1992). *Textilien im Operationssaal – ein Rückblick in das letzte Jahrhundert*, Forschungszentrum Hohensteiner Institute, Bönnigheim.
Hohensteiner Report (2000). *Tragekomfort von Schutz- und Arbeitskleidung im Krankenhaus*, Forschungszentrum Hohensteiner Institute, Bönnigheim.
Hohenstein Test Report (2000). Fabrics for surgical gowns and OR-garment ensembles, Z0.4.3884, Bekleidungsphysiologisches Institut Hohenstein.
ISO 11092 (1993). Measurement of thermal and water-vapor resistance under steady-state conditions (sweating guarded-hotplate test).
Kuno Y (1956). *Human Perspiration*, Charles C. Thomas, Springfield.
Kunze B (1998). Vliesproduktion mit Spunlaid-Technologien, *Vliesstoffe/Technische Textilien*, 29(1/2), 18–25.
Mecheels J (1998). *Körper-Klima-Kleidung*, Schiele and Schön, Berlin.
Mecheels J and Umbach K H (1976). Thermophysiological properties of clothing systems, *Melliand Textilbericht*, 57, 1142–7146.
Mecheels J and Umbach K H (1977). Thermophysiological properties of clothing systems, *Melliand Textilbericht*, 58, 76–85.
Mehnert L and Bernstein U (1996). Mikroporöse Strukturen und ihre Anwewndung für Schutzbekleidung, *Melliand Textilberichte*, 76(4), 263–265.
Randall W C (1946). Quantitation and regional distribution of sweat glands, *J Clin Invest*, 25, 761–767.
Rigby J and Subhash C (1996). Nonwovens in medical and healthcare products, Part 2: Materials and applications. *Tech Textile Int*, 5(8), 24–29.
Schmidtke H (1974). *Ergonomie 2*, Carl Hanser, München.
Träubel H, Schütze D I and Pedain J (1994). Bessere Tragehygiene durch wasserdampfdurchlässige Materialien, *Textilveredelung*, 29(6), 171–177.

© Woodhead Publishing Limited, 2011

21

Occupational clothing for nurses: combining improved comfort with economic efficiency

M. WALZ, Eschler Textil GmbH, Germany

Abstract: The chapter looks at the occupational clothing available for nurses and the possibilities of improved wearer comfort in combination with economic efficiency. It concentrates on the results of a research project, taking the optimisation of the textile material as its subject. In the research project the general and specific requirements of occupational clothing were examined. The questions of how wearer comfort can be defined and measured, and how durable the optimised materials are against multiple industrial washing cycles were investigated. It was possible to develop new materials based on knitted microfibre fabrics, which are superior to standard products on the market.

Key words: knitted workwear, wearer comfort, clean air suits, occupational clothing, cleanliness, optimised textiles, quality standard 704, improved efficiency, sustainability.

21.1 Introduction

Textiles are basic materials at home and in the workplace. They are often not properly considered in more complex working environments. This is particularly true for nurses' occupational clothing, which is worn in different conditions in hospitals. The textile industry needs to develop appropriate research-based solutions to meet these conditions.

21.1.1 Overview of the chapter

The following chapter is divided in three main parts. The first part reviews the requirements for occupational clothing in general and for specific applications. The use of clothing in the operating theatre will be discussed in relation to the requirements of the EN 13795 'Clean Air Suits' standard, including specifications for approved fabrics.

The second part addresses wearer comfort; how wearer comfort can be defined, how it can be measured and the requirements for an acceptable level of comfort. It also examines the ways in which wearer comfort can be improved. The results of a research project are then discussed, including the engineering of fabric for workwear with superior wearer comfort.

The third part addresses the durability of textiles and clothing. It examines the resistance of fabrics to multiple industrial washing and drying, with specific

© Woodhead Publishing Limited, 2011

reference to the mechanical properties and comfort features of fabrics. Examples of existing prototype fabrics are discussed in detail.

With an ageing population and the rising cost for the healthcare systems, cost is becoming a priority. This chapter concludes by discussing the appropriate assessment of costing in the healthcare sector and the impact of ecological issues.

21.1.2 Key issues and requirements of nurses' clothing

General requirements of occupational clothing

Occupational clothing has to fulfil a basic level of requirement, just as regular clothing does. The minimum considerations when designing clothing include, correct fit, style, climate adaptability and ease of washing. Also to be considered are the basic human ecology aspects (e.g. Oeko-Tex® 100) to protect people from harmful substances on the garments, and the ecological aspects of product and production (e.g. bluesign®).

Further to these basic requirements, occupational garments must be designed taking into account cost, durability and functionality in a working environment e.g. protection wear according to EN standards. An expanding textile rental industry, which is supplying garments to companies, requires a variety of different garments to achieve better processability in industrial washing.

Specific requirements of nurses' clothing

Regardless of the ultimate application of the textiles, there are always some requirements which take priority over others. For this reason, some requirements will need to adapt; most of the time leading to a compromise. This is especially true for nurses' clothing, where the priorities of opacity, comfort and style are very high.

The main part of nurses' clothing will be in white or light colours. The fabrics which are used have to be opaque. Together with the style and the appearance of the clothing, these two features will make the wearer feel comfortable even without having any influence on the physiological wearer comfort.

Nurses' activities and physiological stress

The nursing process consists of general and specific patient care procedures, including documentation of relevant health data, assisting of the attending doctors and some medical treatment.[1] This includes high physical strain, for example during the moving of patients. With suitable, functional clothing, this physical strain can be reduced.

Additional requirements for use in the operating theatre

As clothing used in the operating theatre needs to be changed and reprocessed very often, it needs to be unisex and it cannot be personalised. The washing

© Woodhead Publishing Limited, 2011

process is necessary due to the requirement for sterilisation of clothing within this environment; this washing and drying causes stress on the garments due to the high temperatures required.

When it comes to moisture management a high performance fabric will be superior to standard ones, especially when worn under X-ray protective clothing or surgical scrubs. Colour of the fabric also has to be selected in a sensible way, in order not to compromise the light and therefore the visual perception of the surgical team.

Hygiene is of particular importance when it comes to garments worn in the operating theatre. They build a barrier between the nurse and the patient. Linting of breaking fibres will lead to a risk of nosocomial infections, therefore the structure of the fabric is particularly important. A suitable standard EN13795[2] has been set for garments which are used in the operating theatre. The part relating to the Clean Air Suit is particularly relevant, including the linting tendency of a particular material (DIN EN ISO 9073-10),[3] this is the minimum release of particles of the material itself (such as fibres or parts of fibres), tensile strength dry (DIN EN ISO 9073-3)[4] for woven fabric, bursting strength dry (DIN EN ISO 13938-1)[5] for knitted fabric, dry penetration (DIN EN ISO 22612)[6] for the bacteriological barrier. The resilience against penetration by bacteria is distinguished in dry state. Microbial cleanliness (DIN EN ISO 11737-1),[7] and the absence of foreign materials is required. These include microbiological cleanness (bioburden), the cleanness of water-soluble substances and particle material (foreign particles).

21.2 Materials and methods

21.2.1 Description of materials

For the evaluation of new fabric constructions, it is necessary to have a data set of common fabrics with which to make comparisons. As a basis for the test results, a quality woven fabric has been used in the blend of 65/35% PES/CO staple fibre material, with a weight of 215 g/m^2.

Various new constructions have been created and tested. Material 2 is constructed with a blend of 98% polyester microfibre filament and 2% of carbon fibre for additional antistatic properties. The weight is 120 g/m^2 and warp knit technology is used. Material 1 and Material 3 are constructed with a combination of polyester filament yarn and polyester spun yarn, making it a 100% polyester fabric. These fabrics are two-sided and their weights are 215 g/m^2 and 190 g/m^2.

21.2.2 Description of test methods

Test methods used in the research project are described in brief. Industrial washing and drying is done according to DIN EN ISO 15797-2[8] standard, with a defined

© Woodhead Publishing Limited, 2011

number of cycles and process parameters. Marks are added to the fabric to enable a basis for measurement before and after washing and therefore the assessment of the shrinkage according to DIN EN ISO 3759[9] standard.

To measure wearer comfort, different parameters are tested and the wearer comfort grade is then calculated. For the majority of tests a model of the human skin is used for the thermophysiological values.

During the *abrasion resistance test* according to DIN EN ISO 12947-1[10] standard, the fabric is scrubbed on both sides until one single thread is destroyed. Similar to this the pilling test according to DIN EN ISO 12945-2[11] standard is executed. After a defined number of scrubbing turns, the surface is evaluated.

For the *snagging test* according to the ICI-method, the samples are put in a box which is continuously turned. Inside the box the samples fall randomly on spikes and the snags caused are assessed.

For the *bursting strength test*, samples with a surface of 7.3 cm^2 are attached on a rubber plate. The pressure under the rubber plate rises until the fabric is destroyed. The amount of pressure gives a value for the assessment of fabric strength according to EN ISO 13938 standard.

21.3 Cleanliness

The developed fabrics passed the tests for Clean Air Suits,[12] with specific reference to use in the operating theatre. They reached the high performance level of cleanliness required, with single values for Material 1 of IPM 2.91 inside and 3.29 outside, and values of IPM 3.43 inside and 2.17 outside for Material 2. In addition to this, the single values for the linting tendency of Material 1 of $\log_{10}$ 3.09 inside and 3.51 outside and of Material 2 of $\log_{10}$ 3.66 inside and 2.55 outside enabled the fabric to be suitable for the high performance level.

Material 2 also passed the dry penetration test with a single value of 30.7 KBE and 1.49 log, as well as the cleanliness microbial test with a value < 2 log KBE/dm^2. In the following sections these two materials will be described with regards to their performance in durability, efficiency and wearer comfort.

21.4 Improving comfort in nurses' occupational clothing

21.4.1 Defining wearer comfort

Clothing with good wearer comfort supports the regulation of the body temperature. The human body regulates its temperature in two different ways. To keep the body warm, the blood vessels of the skin narrow to minimise heat loss on the surface. As this is not very effective, in most areas of the world it is necessary to wear clothes to keep the temperature stable. If the person begins physical

© Woodhead Publishing Limited, 2011

activities, or the surrounding conditions change to a higher temperature, the body needs to cool down to keep its body temperature at 37°C. Therefore the blood vessels will widen to enable more heat to diffuse out. The skin can also produce sweat on its surface to speed up the cooling process. The body's actions can sometimes be blocked by unsuitable clothing, which leads to a higher body temperature, resulting in more physical stress on the body. People start feeling uncomfortable if the system of human body and garment is not functioning properly. Suitable, comfortable clothing goes unnoticed by the wearer; only when garments cause discomfort does the wearer become aware of their presence. Wearer comfort can be defined as the determination of the physiological strain on the individual depending on clothing, climate and activity.

21.4.2 Measurement of wearer comfort

The Hohenstein Institute's research into the science of the physiological function of clothing has gained international recognition. Various biophysical measuring devices are used for the quantitative assessment of the wear properties of clothing systems – such as workwear and industrial clothing (Table 21.1).

Quantitative measurement and assessment of the wear comfort of textiles and clothing has been undertaken, which enables the Institute to calculate a specific mark for each specific application. The guideline values are based on the research results of the Hohenstein Institute, gained in various surveys, including tests with participants.

Table 21.1 Guideline values for wearer comfort in workwear

Parameters	Guideline values
Thermophysiological parameters	
Rct = thermal resistance	10 to 20 × 10 h^{-3} m^2K/W
Ret = water vapour resistance	< 8 m^2Pa/W
imt = water vapour index	>0.15
Fd = buffer action ex vapour phase	>0.4
Kf = buffer action ex liquid phase	>0.78
F = sweat transportation per hour	>765 g/m^2
Sensory parameters	
iK = stick index	<15
iB = wetting index	<270
iO = surface index	3 to 9
nK = number of contact points	<1500
S = stiffness	<60°
Wearer comfort grade	
Thermophysiological comfort grade	<3.0
Sensory comfort grade	<3.0
Combined comfort grade	<3.0

© Woodhead Publishing Limited, 2011

21.4.3 Description of possible changes in the textile construction to improve comfort

Textiles can be specifically engineered to fulfil the requirements of particular garments. Very often the functions have a strong influence on each other, so that the result will always be a compromise. It is the responsibility of the textile industry to find out the needs of the wearer and optimise the textile system to meet these priorities.

Improvements on wearer comfort are a consideration for the whole textile chain. Garments are based on the raw material, the fibre and yarn construction, the textile processing, the dyeing and finishing, and the design. Changes are possible in each step of the process.

Keeping the general workwear and specific nurses' requirements in mind, only a few modifications make good sense. The best material to use is polyester, due to its basic properties. The yarn construction will improve the comfort if changed to fine filament microfibres. These will not trap the moisture on the inside of the fibre, but will instead transport it to the outside of the garment and store it in the spaces between the fibres. It will therefore dry off much easier compared to natural fibres. To support this effect, the construction can be changed to a two-sided fabric, which will physically push and pull the moisture to the outside, due to the capillary effect generated by a different diameter of the single fibres. The finer the microfibres, the more moisture can be stored. They will also create a much softer hand compared to standard workwear.

Using filament yarns will increase the mechanical resistance and produce less linting during use. If the inner surface of the textile can be engineered to build out small spacers, it will prevent the sensation of the fabric sticking to the skin and improve the absorption of sweat.

The fabric needs to have a porous construction. Dense woven materials will limit the amount of radiant heat which can diffuse out and reduce breathability. Whereas knitted fabrics are generally more breathable than densely woven fabrics which weigh the same, due to being constructed of stitches. These stitches will additionally supply some stretch performance to the fabric.

Permanent hydrophilic treatment is another important improvement which can be made to fabrics. With this treatment, moisture can be absorbed easily by the fabric and transported to the outside of the garment. Reprocessing must be carried out in order to keep the finishing at the same level as in the beginning of the garments' lifecycle. Every treatment with chemicals has to be managed with consideration of the fabrics properties. For example, fabric softener will often create a hydrophobic surface. All these modifications create functional fabrics, similar to those used in the sports industry. The difficulty here is to combine the demands of both worlds: occupational clothing and functional sportswear.

© Woodhead Publishing Limited, 2011

21.4.4 Results of research project ProInno: comparison of standard product with various optimised textiles

Eschler Textile and The Hohenstein Institute undertook a research project for the improvement of wearer comfort for workwear in the healthcare sector during 2008 and 2009. During this project, various new fabric constructions were produced and measured in comparison to the standard fabric on the market, consisting of quality woven fabric in the blend of 65/35% PES/CO staple fibre material. It was verified that the all-over wearer comfort can be improved from the mark 2.2 to a maximum of 1.1.

Material 2 consisted of a blend of microfibre filament and 2% carbon fibre, for additional antistatic properties. The weight of 120 g/m^2 and the warp knit technology make Material 2 very different to standard woven fabrics, which are made of blends of cotton and spun yarn. The values for the thermo-physiological parameters of Material 2 are significantly different, which will lead to an obvious difference for the wearer (see Table 21.2). The thermal resistance of 9.4 is around 30% below the standard fabric, and the water vapour resistance of 1.85 is, with a factor of around 1.7, also clearly below.

Table 21.2 Wearer comfort of optimised textiles in comparison to a standard product

Test/norm	Standard quality fabric	Material 1	Material 2	Material 3
Thermophysiological parameters				
R_{ct}	15.7	18.7	9.4	12.4
R_{et}	3.22	3.19	1.85	3.25
i_{mt}	0.29	0.35	0.3	0.23
F_d	0.56	0.57	0.61	0.58
K_f	0.86	0.99	0.96	0.97
F_1	20.1	20.3	23.9	20.5
F	812	820	966	828
G_2	5	6.9	5	6.4
$\Delta G_{(rel)}$	31.4	44.7	54.5	40.5
Sensory parameters				
i_K	17.1	10.9	2.8	8.2
i_B	>600	1	1.4	0.2
i_O	3.2	3.9	1.6	2.6
n_K	1359	1512	1586	1614
s	31.0	25.3	18.8	29.4
Wearer comfort grade				
$TK^{(T)}$	—	1.8	1.1	1.7
$TK^{(S)}$	—	1.3	1.1	1.9
$TK^{(combined)}$	2.2	1.6	1.1	1.8

© Woodhead Publishing Limited, 2011

In the results for the sensory parameters, Material 2 again outperforms the standard fabric, especially in results for the stick index at 2.8, the wetting index at 1.4 and the stiffness index showing a value of only 18.8.

These single values confirm the overall comfort grade of 1.1 for Material 2. Material 1 and Material 3 consisted of a combination of polyester filament yarn and polyester spun yarn. The touch, look and weight are more similar to the standard fabric than Material 2, but due to the knitted construction they feel much softer. The difference between Material 1 and Material 3 is that the latter was optimised for better wearer comfort, by reducing the weight from 215 g/m^2 down to 190 g/m^2 and by using slightly coarser yarns with a lower diameter in the single fibre.

Compared to the standard fabric, the thermal resistance, R_{ct}, value of both materials was reduced as predicted; however, other values did not improve and actually performed worse than before in some cases. The grade for thermo-physiological comfort achieved was 1.7, which is an improvement of 0.1 on the standard fabric. However, the grade for sensory comfort dropped by 0.6 to a grade of 1.6. This led to a combined comfort grade of 1.8, which is still better than the standard, but lower compared to Material 1.

21.5 Improving durability of nurses' clothing in industrial laundering processes

21.5.1 General description of procedure with reusable textiles

Textile rental service firms provide healthcare facilities with a wide variety of specialised textiles, including textiles for the operating theatre, as well as clothing for patients and staff. Reusable medical textiles have to perform to the high standards of the healthcare professions in terms of hygiene, suitability, safety (for patients and hospital staff), comfort and traceability.

The cycle for reusable textiles follows a series of steps. First, the clothing will be worn. When the garment is changed it goes into a bin or locker, where it will be collected by the leasing company. The minimum period before changing nurses' occupational clothing is once per day. If a visible contamination occurs it has to be changed immediately. Even more changes will take place in the operating theatre. Each time people leave and re-enter the sterile environment, their clothing is required to be changed. Therefore, many pieces of clothing have to be in the cycle to ensure availability.

The leasing company will give the garments to a professional laundry, where it is washed and dried under qualified programmes. It will then be inspected for damage and repaired or exchanged if required. After sorting and packaging it will be brought back to the hospital and placed into wardrobes from which the textiles are issued. With general occupational clothing the garments are personalised, meaning that the same garments will be given to the same personnel every time.

© Woodhead Publishing Limited, 2011

In the operating theatre, however, it is not possible to personalise the garments, as they are changed too often. Here the cut of the clothing has to be unisex and the clothing is distributed to the personnel out of a bulk lot.

More than simply renting, cleaning and repairing textiles, rental companies offer customer-tailored service solutions. This can support hospital managers in terms of internal logistics and textile management, in order to lower costs and optimise textile inventory.

21.5.2 Measurement and guideline values of capability for industrial washing

The Hohenstein Institute has announced a quality standard for garments used in the leasing industry. These standards have been evaluated on the basis of technical limitations of the textile industry and the requirements of the cleaning companies. The Quality Standards 701ff define minimum requirements for textiles; if these are met, it can be assumed that the textiles are suitable for industrial processing. The Quality Standard 704 shows data for polo shirts and shirts. Table 21.3 shows

Table 21.3 Hohenstein Quality standard 704: Guideline values for industrial washing

Test	Test method	Staining	Colour change
Fastness to water	DIN EN ISO 105 E01	≥ 4	≥ 4—5
Fastness to sweat	DIN EN ISO 105 E04	≥ 3—4	≥ 4
Fastness to rubbing	DIN EN ISO 105 X12	dry, ≥ 4; wet, ≥ 3	–
Fastness to washing	Following 105-C06/E2S with 1:5	≥ 4	≥ 4
Fastness to washing with hypochlorite	DIN 54016	≥ 4	≥ 4
Fastness to bleaching with hypochlorite	DIN EN ISO 105 N01	–	≥ 4
Fastness to bleaching with peroxide	DIN EN ISO 105 N02	≥ 4	≥ 4
Combined fastness to washing/dry heat	Fixotest 5 min, 190°C, DIN EN ISO 105 C05	≥ 3–4	≥ 4
Light fastness	DIN EN ISO 105 B02	–	≥ 5
		Minimum requirement	
Bursting strength	EN ISO 13938	600 kPa	
Abrasion resistance	DIN EN ISO 12947-1 (both sides)	25 000 turns	
Pilling	DIN EN ISO 12945-2 (after five cycles EN15797)	2–3 (7000 turns); 3 (5000 turns)	
Snagging	ICI	≥ 4	
Shrinkage	DIN EN ISO 3759, DIN EN 25077 (after five cycles EN15797)	+3% to –5.0%	
Self-smoothing	DIN EN ISO 15487 (after three cycles EN15797	>50% CO, ≥ 3.0; <50% CO, ≥ 3.5	

© Woodhead Publishing Limited, 2011

the mechanical properties of the textile materials, including colourfastness, resistance of the findings and reprocessability in textile service companies. For the survey of improved nurses' clothing, the requirements regarding colourfastness were not taken into account. As all developed fabrics are based on polyester, the colourfastness standard required can be generally achieved.

Beside the Hohenstein Quality Standard, another guideline for workwear fabrics used in the leasing industry has been developed. The European Textile Service Association (E.T.S.A.) published the E.T.S.A. requirements, which cover woven fabric made of polyester/cotton blends with a weight of 150 g/m^2 to 400 g/m^2 and is very similar to the Hohenstein Standard regarding the tests for physical and colour performance. Particularly in the operating theatre, the new generation of wearer comfort and hygienically improved clothing are made of lightweight, synthetic fabrics. So, the E.T.S.A. requirements are not all applicable, but will suit as a general guideline. These requirements need to be interpreted correctly by textile experts.

21.5.3 Description of possible changes in textiles to improve efficiency

As mentioned above, the engineering of textiles to improve the functions required is feasible, but very often this will weaken the other properties of the fabrics. Therefore, a compromise with clear priorities must be the result.

Improvements on durability of textiles will, in general, be achieved using coarser yarns and increased fabric weight. Eschler decided to develop only fabrics based on synthetic material, as they can combine high performance on comfort, hygienic standards and durability at a much lower weight than natural fibres. Though this is not a new idea in the textiles industry, many people still refuse to wear synthetic fabrics. This thinking is widely spread in hospitals.

The measurements of the materials specifically developed for the research project showed very good results compared with the Hohenstein quality standard 704, even though they had been designed to feature a superior wearer comfort.

Material 2, with the best wearer comfort grade 1.1, easily exceeded the recommended value of a minimum of 600 kPa for the bursting strength standard DIN EN ISO 13938 with 876 kPa. The Pilling standard DIN EN ISO 12495-2 showed very good marks of 4–5 on the inside and the outside, compared to the required marks of 2–3. The same good results were achieved in the snagging test ICI-method with the mark 4. Two single values had not been satisfactory on the first attempt. The test for the abrasion resistance standard DIN EN ISO 12947-1 requires 25 000 turns for woven garments. This standard was not quite reached, with a value of 20 000 turns. For a lightweight, knitted fabric it is a very good result and close to the guideline for woven material. The washing shrinkage showed −4.5% after five washing cycles and again is within

© Woodhead Publishing Limited, 2011

Table 21.4 Test results of optimised materials relating mechanical properties

Property	Test method	Material 1	Material 2
Bursting strength	EN ISO 13938	892.4 kPa	876.4 kPa
Abrasion resistance	DIN EN ISO 12947-1 (both sides)	20 000 turns	20 000 turns
Pilling	DIN EN ISO 12945-2 (after two cycles EN15797)	Outside 4; Inside 3–4	Outside 4–5; Inside 4–5
Snagging	ICI	4	4
Shrinkage	DIN EN ISO 3759, DIN EN 25077 (after five cycles EN15797)	–2.56%	–4.5%
Self-smoothing	DIN EN ISO 15487 (after three cycles EN15797)	3.5	3.5

the guideline for knitted fabrics, but just misses the requirements for woven fabrics.

Material 1 achieved a combined wearer comfort of 1.6 with a weight of 215 g/m^2. The appearance of the knitted fabric is completely different to Material 2; it more closely resembles the standard fabric. Due to the knitted textile structure the hand and feel of Material 1 is much softer than woven fabrics. From a mechanical point of view, the figures show very good results. The bursting strength test with a mark of 892 kPa, the pilling test with marks of 3–4 inside and 4 on the outside, the snagging test with a mark of 4 and the shrinkage of –2.5% after 5 cycles, at the standard EN15797, are all clearly above the requirements. Only the abrasion resistance, with a value of 20 000 turns, is under the value required. As occupational clothes based on knitted fabric constructions are new to this market, they will have to be proven in trials under real work conditions (Table 21.4).

Tests undertaken in the laboratory can only help during the development stage of special textiles. Washing and wearing trials are then essential for the approval of the clothing. The performance of the garments will be influenced by a number of different factors such as the type of washing and drying programs used.

With respect to profitability, the quality and thus the potential service life of textiles for leasing (rental textiles) are particularly relevant.

21.5.4 Results of research project ProInno: improved efficiency in combination with improved wearer comfort

The goal of the research project was to design a fabric, which is superior to standard products on the market in relation to wearer comfort, whilst maintaining performance after processing in industrial laundries. To compare the two fabrics' durability they were processed in the laboratory of the Hohenstein Institute according to the EN 15797 standard, up to 75 cycles.

© Woodhead Publishing Limited, 2011

To obtain information of the mechanical durability of the new fabrics, some tests were repeated after the washing cycles. One important test is the bursting strength test. This test shows the deterioration of the used materials and yarns regarding strength. The results of all three materials show significant values.

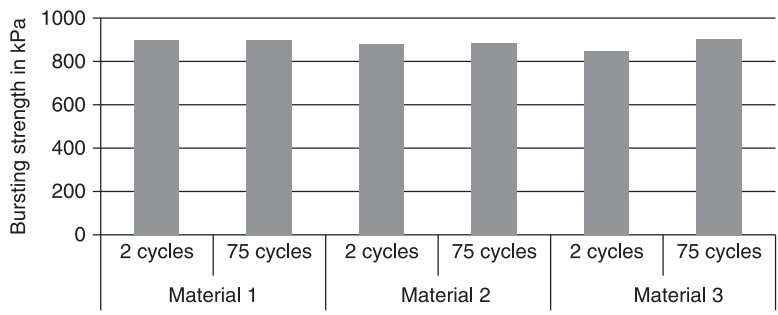
Material 1 and Material 2 show no loss of strength at all. Within the measuring accuracy the figures are exactly the same, at 892 kPa (Material 1) and 877 kPa (Material 2). Material 3 began with a bursting strength of 842 kPa; this value actually increased after 75 cycles, to 899 kPa. This can be attributed to the shrinkage caused by washing, which took place from the first two cycles to the 75th cycle. The density, and consequently the number of yarns per test area, increased.

By taking the small shrinkage of Material 1 of −5.6% and Material 2 of −3.5% after 75 washing and drying cycles into account, the loss in strength can be estimated to values of around 5% after 75 cycles (Fig. 21.1).

Another test to obtain information for the durability of the materials surface is the pilling test. Changes on the surface structure are assessed. Again, the results of all three materials show significant values. Looking at the values for the outside of the materials, the marks did not change after washing cycles. The value for Material 1 rose from 4 to 4–5, whilst the values for Material 2 and Material 3 stayed exactly the same at 4–5 before and after the repeated processing (Fig. 21.2).

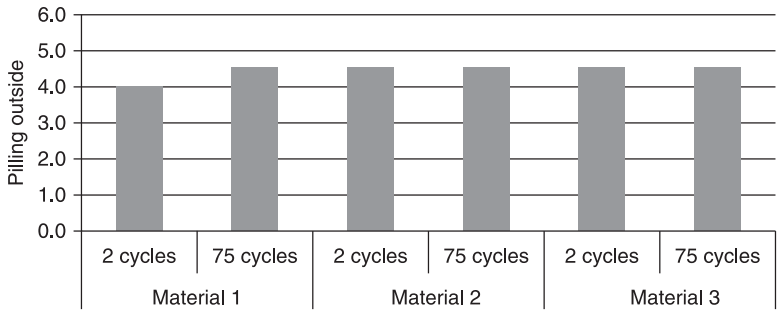
In addition to the mechanical testing, various scanning electron micrographs were taken to show the alteration of the fabric's surface. For Material 1, some breakages of very fine microfibres are visible. These few fibres are evenly spread. When compared to the picture after 75 cycles, there are only a few additional loose fibres. Some minor accumulations were starting to form. However, the surface still showed no pills, as the pilling test data proves.

Material 2, consisting of 100% filament yarns, performed even better. No difference can be seen before and after the repeated processing. Very few loose



21.1 Comparison of bursting strength values after 2× and 75× processes according EN 15797.[7]

© Woodhead Publishing Limited, 2011

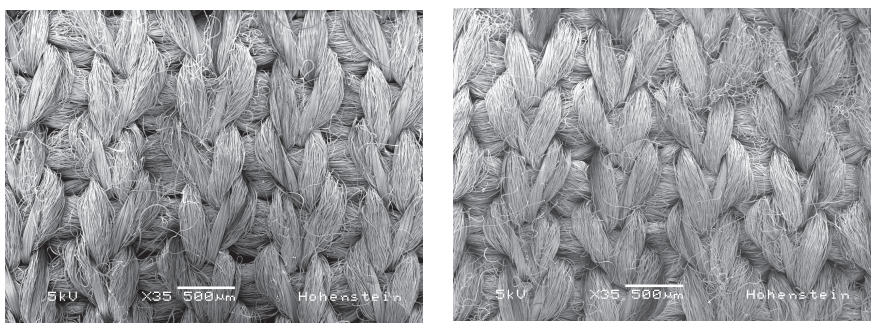


21.2 Comparison of pilling values after 2× and 75× processes according EN 15797.[7]

fibres were showing. For the construction of Material 2, an antistatic thread with a carbon filament was used. The carbon part is clearly visible on the SEM picture. As the antistatic properties were not being measured within the research project ProInno, they have not been measured before and after washing. However, the SEM scans show no deterioration of the carbon fibre at all. This leads to the estimation that the antistatic function is durable to the washing process and will continue throughout the product life of the garment (Fig. 21.3 and Fig. 21.4).

The intention of the research project is to help to develop superior occupational clothing, combining suitable workwear fabric with optimised wearer comfort. Therefore, the properties required for superior wearer comfort must also be able to withstand the stress of multiple processing. For this reason, several tests were repeated after 75 cycles.

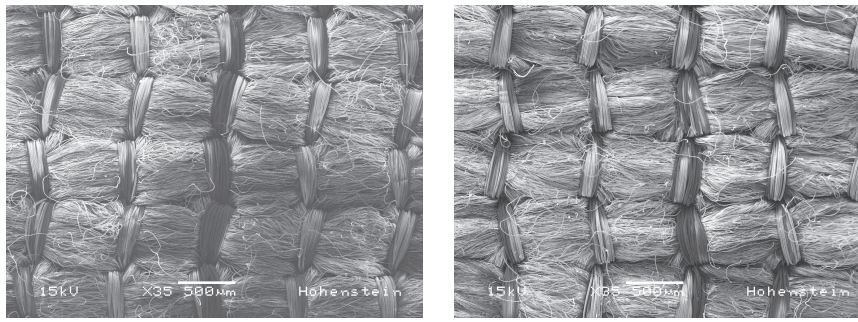
For the thermo-physiological measurements, the sweat transportation, F, was chosen as a marker. The sweat transportation per hour, F, should give a minimum value of 765 g/m^2. Material 1 showed a minor drop, starting at 820 g/m^2 after two



(a) (b)

21.3 Material 1: Visualisation of fabric surface after 2× and 75× cycles.[7]

© Woodhead Publishing Limited, 2011

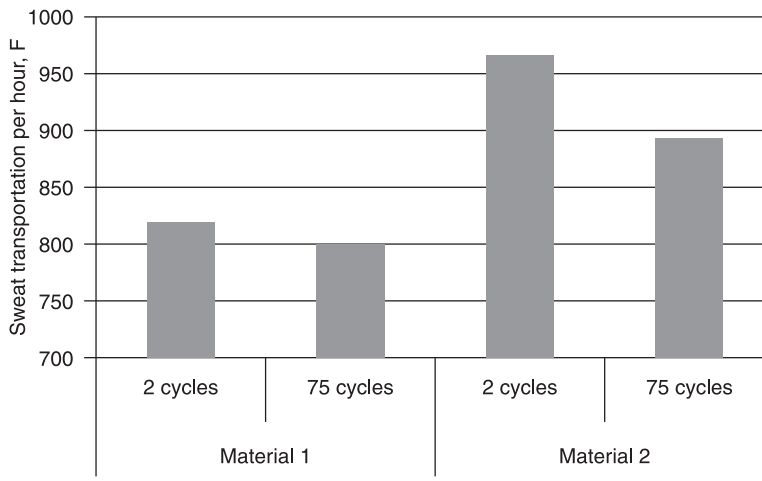


(a) (b)

21.4 Material 2: Visualisation of fabric surface after 2× and 75× cycles.[7]

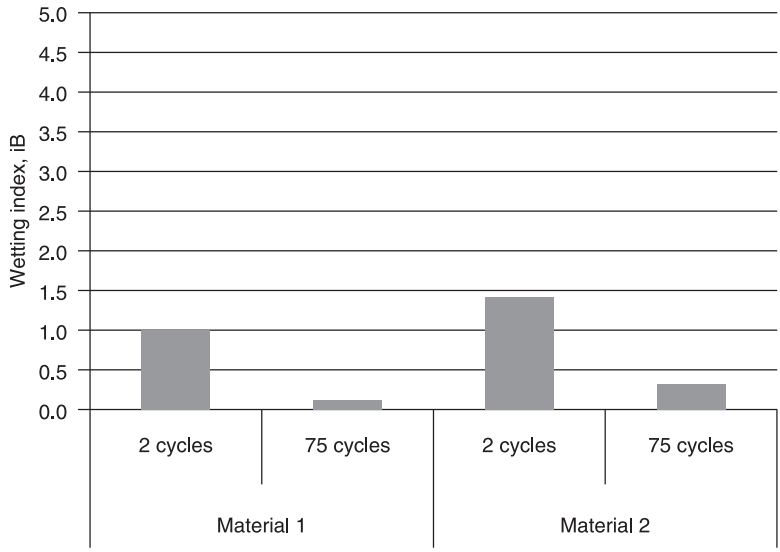
cycles, decreasing to 800 g/m^2 after 75 cycles. This corresponds to a diminution from 'very good', down to 'good'. Material 2, which was the best fabric in terms of wearer comfort, dropped in this value from 966 g/m^2 down to 893 g/m^2. Although this seems like a large drop, as the starting value was initially high, the second value is still distinctively better than 'very good'.

For the sensory parameters, a comparison of the wetting index, iB, was selected. The guideline values give a maximum of 270. Both materials performed far better than the recommended figure, even after 75 cycles. From these results, it can be seen that both materials would maintain very good wearer comfort throughout their life cycle (Fig. 21.5 and Fig. 21.6).



21.5 Comparison of sweat transportation values after 2× and 75× processes according to EN 15797.[7]

© Woodhead Publishing Limited, 2011



21.6 Comparison of wetting index values after 2× and 75× processes according to EN 15797.[7]

21.6 Possible savings in resources, washing and drying, durability and nosocomial infections

The research project has indicated that highly functional fabrics made of polyester can fulfil all the requirements for the rental industry, combined with very good wearer comfort and hygiene standards. The cost of such innovative garments would be higher at the point of purchase, but the use offers potential savings, compared with conventional occupational clothing.

If textiles made from synthetic fibres were leased to hospitals, the management costs would be significantly lower and the rental companies would be able to supply a full service package. There would be savings in laundry, due to lower energy consumption while drying the garments. Because the synthetic fibres do not absorb moisture as much as natural fibres, they dry more quickly. An Eschler internal test has shown an energy consumption of only 30% compared to standard fabrics. In general, synthetic fibres will also perform better than natural fibres, when it comes to the durability. Longer lasting textiles would mean that fewer repairs would be necessary throughout the life cycle of the garment.

In Germany between 525 000 and 1 000 000 nosocomial infections occur every year. This is then the most common kind of infection in German hospitals. The new clothing developed according to the EN 13795 standard has the potential to reduce these incidents, as fewer particles will be released into the hospital

© Woodhead Publishing Limited, 2011

environment. These particles can transport microorganisms, therefore if their spread can be reduced this will lead to an improvement in hygiene levels.

In Germany, hospitals are paid in case-based lump sums. So, the length of a patients stay will directly influence the cost, and therefore the earning for the hospital. Taking all these considerations into account, it is assumed that the higher purchasing cost of textiles will be balanced throughout their use.

21.7 Applications of knitted microfibre fabrics

21.7.1 Nurses' occupational clothing: general use

Smock overalls and trousers for nurses' occupational clothing can be made of knitted, microfibre fabric. The garments can retain their traditional cut and style (like Material 1; Fig. 21.7).

21.7 Nurses' occupational clothing by Karl Dieckhoff GmbH & Co.KG, made of microfibre material.[10]

© Woodhead Publishing Limited, 2011

21.7.2 Clothing for the operating theatre

The standard EN 13795 Clean Air Suit should be considered when designing new innovative garments for the operating theatre. Good wearer comfort also has to be incorporated. Clothing made of lightweight microfibre, such as Material 2 mentioned above, is ideal for this application (Fig. 21.8).

21.8 Clothing for the operating theatre by Karl Dieckhoff GmbH & Co. KG, made of microfibre material.[10]

21.8 Future trends

21.8.1 Need of cost-savings in the medical sector

With an ageing population, the cost for healthcare will rise during the next decades. More people will need medical treatment and assistance as they grow older. At the same time fewer people will pay health insurance. Therefore, in order to maintain a fair and social system, the pressure on cost reduction in the medical sector is growing. To face the problem, the German health system has been reorganised. German hospitals are now paid in case-based lump sums. So, the length of a patients' stay will directly influence the cost, and therefore the earning, for the hospital.

21.8.2 Integrated consideration in the operating theatre and hospital

The selection of medical textiles and occupational clothing in the operating theatre and hospitals is very complex. Many factors have to be examined.

© Woodhead Publishing Limited, 2011

General conclusions are difficult; each case has to be surveyed by its own requirements.

Very often, decisions are made on purchasing costs alone, not taking into account hidden savings such as lower investment, operating costs, waste disposal and transparency of consumption for the rental system. Calculations for better performance on the job and the reduction of nosocomial infections are scarcely feasible.

21.8.3 Multifunctional textiles

The trend for the future will lead us to multifunctional textiles. Combinations of durability and comfort will be complemented by permanent functions such as antistatic, antimicrobial and soil release effects. Smart textiles will improve patient care further. Major improvements have been made in the integration of electronic devices into textiles. With these textiles, the body's functions can be monitored. These devices can then alert healthcare staff immediately if a patient's health is deteriorating.

21.8.4 Sustainability

From an ecological perspective, different fibres can have different effects. Comparing synthetic fibres with natural fibres, the floor space required for the production of 1 ton of fibres is, for example, 67 hectare for wool, 1.3 hectare for cotton and 0 for synthetic fibres. The water consumption for 1 ton of fibres is 25 000 m^3 for cotton and 4 m^3 for polyester. Synthetic fibres are based on crude oil, utilising 0.8% of the general worldwide consumption. However, partially or completely recycled polyester yarns are available on the market.[4]

There are various eco-labels on the market at present for textiles production. One example is bluesign® which is based on the best available technology. Certified companies can only use tested and approved raw materials. The complete production site must follow an ecological route.

Cambridge University calculated in its study 'Well dressed?' that 60% of the carbon dioxide output of a cotton T-shirt is created after 25 washes. This is due to the high energy output whilst drying and ironing.[17]

E.T.S.A. commissioned a Life Cycle Assessment of surgical gowns. The study assessed the impact of both reusable and disposable gowns. The assessment shows that when all factors are taken into consideration, including costly disposal of hospital waste, the reusable solution is significantly better for the environment. The reason is the lower consumption of energy, water and chemicals. However, there is more to be considered; because reusable surgical textiles cause less waste and emissions, they have considerably less impact on global warming and over-acidification.[18]

Reusable textiles and rental laundries have a positive influence on the regional economy and offer an important contribution to domestic industry.[19,20] In addition

© Woodhead Publishing Limited, 2011

to the cost and quality of medical textiles, their impact on the environment should become a serious factor in the decision-making process.

21.9 Sources of further information and advice

Producers

Karl Dieckhoff GmbH & Co. KG, DE-42389 Wuppertal, www.dieckhoff-textil.de
Bierbaum-Proenen, GmbH & Co. KG, DE-50668 Köln, www.bp-feelthedifference.com
Alsico, BE-9600 Ronse, www.alsico.be
Sioen-Med, BE-8850 Ardooie, www.sioen.be

Leasing companies/rental laundries

LEO System GmbH, DE-58239 Schwerte, www.leo-system.net
Opalys GmbH, DE-96231 Staffelstein, www.opalys.de

Institutes

Hohenstein Institute, www.hohenstein.de
wwH-c GmbH, www.wwH-c.com
HygCen – Centrum für Hygiene und medizinische Produktsicherheit GmbH, www.hygcen.de

Associations

Industrieverband Textil Service e.V., www.intex-med.de
Industrievereinigung Chemiefaser e.V., www.IVC-eV.de
European Textile Services Association, www.etsa-europe.org

Internet

bluesign technologies ag, www.bluesign.com
Funktionstextilien-online, www.funktionstextilien.de
Oeko-Tex® Standard 100, www.oeko-tex.com

21.10 Acknowledgement

The author acknowledges funding for the mentioned research project via grant No. PRO INNO 2 F0125504UL7 of the Arbeitsgemeinschaft industrieller Forschungsvereinigungen Otto von Guericke e. V.

© Woodhead Publishing Limited, 2011

21.11 References

1 Job description nurse, http://berufenet.arbeitsagentur.de/berufe/start?dest=profession&prof-id=27354.
2 DIN EN 13795 1–3:2009: Surgical drapes, gowns and clean air suits, used as medical devices for patients, clinical staff and equipment.
3 DIN EN ISO 9073-10:2005-03: Textiles – Test methods for nonwovens – Lint and other particles generation in the dry state.
4 ISO 9073-3:1989-07: Textiles – Test methods for nonwovens – Determination of tensile strength and elongation.
5 DIN EN ISO 13938-1:1999-10: Textiles – Bursting properties of fabrics – Part 1: Hydraulic method for determination of bursting strength and bursting distension.
6 DIN EN ISO 22612:2005-03: Clothing for protection against infectious agents – Test method for resistance to dry microbial penetration.
7 DIN EN ISO 11737-1:2006-04: Sterilization of medical devices – Microbiological methods – Determination of a population of microorganisms on product.
8 DIN EN ISO 15797:2002: Textiles – Industrial washing and finishing procedures for testing of workwear.
9 DIN EN ISO 3759:2008-05: Textiles – Preparation, marking and measuring of fabric specimens and garments in tests for determination of dimensional change.
10 DIN EN ISO 12947-1-4:2007-4: Textiles – Determination of the abrasion resistance of fabrics by the Martindale method.
11 DIN EN ISO 12945-2:2000-11: Textiles – Determination of fabric propensity to surface fuzzing and to pilling.
12 HygCen Prüfbericht SN 9787, 22.12.2009.
13 ProInno 2-Vorhaben Nr.KF0125504UL7, Institut Hohenstein e.V., Eschler Textil GmbH.
14 Hohensteiner Qualitätsstandard 701ff., Hohenstein Institute.
15 Karl Dieckhoff GmbH & Co.KG, DE-42389 Wuppertal.
16 Chemiefasern-Ein Beitrag zur ökologischen Zukunft, Industrievereinigung Chemiefaser e.V., 20.09.2007.
17 Well dressed? The present and future sustainability of clothing and textiles in the United Kingdom. University of Cambridge, Institute for Manufacturing.
18 E.T.S.A.: Life Cycle Assessment of Surgical Gowns (2000).
19 http://www.intex-med.de/fileadmin/user_upload/intex_med/Dokumente/Infodienst_01.pdf.
20 http://www.intex-med.de/fileadmin/user_upload/intex_med/Dokumente/Infodienst_03.pdf.

© Woodhead Publishing Limited, 2011

22

Medical bandages and stockings with enhanced patient acceptance

C. ROTSCH, H. OSCHATZ, D. SCHWABE, M. WEISER and U. MÖHRING, Textile Research Institute Thuringia-Vogtlande. V., Germany

Abstract: Many therapeutic effects in medicine are achieved through textiles fitted or enclosed on body parts as elastic bandages and stockings. The task for these textiles used as adjuvant during therapy of venous or lymphatic vascular system diseases is the realisation of a defined compression effect on the affected body areas and with it the directed removal of liquids. This chapter discusses textile structures used for venous or lymphatic diseases. Several textile constructions are described as well as indications, applications, measuring methods and, finally, future trends are examined.

Key words: elastic bandages, compression stockings, compression textiles, compression therapy, pressure measuring systems.

22.1 Introduction

Many therapy effects in medicine are achieved through textiles fitted or enclosed on body parts as elastic bandages and stockings. Bandages are used for a directed compression and/or safeguarding of function (stabilisation, control of movement) of body parts or single joints (Spitzenverbände der Krankenkassen, 2008). A partial generation of pressure can be realised by pads. The task of elastic bandages is the fixation of wound dressings (fixation bandages), the compression (compression bandages) and the complete or limited immobilisation of body parts (suspensory/support bandages). According to the indication, elastic bandages can be manufactured with different force–elongation behaviour. Compression stockings can be used as a compression appliance for the impact on the venous or lymphatic vascular system during the complex physical anti-oedema therapy too. Furthermore, textiles fitting or enclosing body parts with a compression effect can be used for the treatment of postoperative or burn cicatrices in different appearances (as tubes for arms and legs, compression bandages, compression bras, etc.).

This chapter discusses textile structures used for venous or lymphatic diseases. Several textile constructions are described as well as indications, applications, measuring methods and, finally, future trends are examined.

© Woodhead Publishing Limited, 2011

22.2 Key issues and role of medical bandages and stockings

22.2.1 Applications of medical bandages and compression textiles

The task for textiles used as adjuvant during therapy of venous or lymphatic vascular system diseases is the realisation of a defined compression effect on the affected body areas and with it the directed removal of liquids. Flexible textile structures like stockings or bandages are applied enclosing the affected body parts with preliminary tension and a defined pressure pattern. According to therapy and the clinical picture, the resulting compression pressure during rest and movement of the patient is interesting.

The resulting compression pressure is influenced by the type of medical therapy (which means the type of compression device used and the appliance) and the force–elongation behaviour of the textile structure. The reset force of the textile structure has to release the medically decreed compression effect to the body during wearing. For this, the defined and reproducible adjustment of the textiles' force–elongation behaviour is essential.

Besides the desired compression pressure or pressure pattern respectively, which should be verifiable with suitable test procedures, ecological safety and good wearer comfort are necessary for high patient acceptance and thus, the desired success of therapy. In addition to the use textiles for compression as a medical therapy, their commercial use as products for healthcare, injury prevention or performance improvement in sports represents an interesting and significant market.

22.2.2 Medical background of compression therapy: venous and lymphatic diseases

Compression therapy is used in various diseases, such as lymphatic or venous insufficiency, lipoedema or even in scars therapy as the only treatment or it is used as part of a complex treatment programme. Varicose veins, chronic venous insufficiency and lymphoedema are the most common indications for compression therapy treatments.

Varicose veins and chronic venous insufficiency

Varicose veins are sac-like, extended and tortuous superficial veins usually of the lower extremity. Based on clinical criteria a distinction in the following main forms of the primary varicose veins can be made:

- Spider veins, microvarices
- Varicoses of the perforating veins

© Woodhead Publishing Limited, 2011

- Reticular varicose veins
- Side branch varicoses
- Trunk varicoses.

The individual varicose types can occur individually or together with other forms.

Typically, there are four different stages of varicose veins, depending on the severity and occurring reflux. An important aspect is an insufficiency of the venous valves. They can not close properly. Thus, it comes to the reflux of venous blood and a barrier or a decrease in the bloodstream.

In contrast, chronic venous insufficiency (CVI) is characterised by chronic reflux disorder of blood from the peripheral to the central vein with subsequent venous hypertension and resulting changes in particular in the areas of the skin. The term 'CVI' allows no conclusion as to the causes of the disease. For characterisation and classification, different scales or principles exist. Three stages according to Widmer can be used for the classification of CVI in daily practice:

- *Stage I*: evening tendency to swelling
- *Stage II*: stage I + trophic disorders, hyperpigmentation (congestive oedema, dermatosclerosis)
- *Stage III*: stages I and II + acute or healed venous leg ulcer.

The more complex CEAP classification is used instead of the three-stage classification by German-speaking countries, too. In addition to the clinical symptoms (C), a classification according to the aetiology (E), anatomical (A), and pathological (P) terms is implemented. So, the inclusion of other factors is possible and thus allows a more accurate description of the individual medical case (Partsch, 2002, 2007; Wuppermann, 2002).

Lymphoedema

The function of the lymphatic system, besides the immunological function, is the disposal of the interstitium. Proteins, water, fats and cells or cell components are removed via the lymphatic system. A lymphoedema occurs as a swelling and increasing hardening of the connective tissue by an interruption of the lymph drainage.

The cause may be a (rare) congenital interruption of the lymph drainage, the so-called primary lymphoedema. In most cases the lymph vessels are anatomically or physiologically incorrectly developed, and the drainage is disturbed. In the more common case – secondary lymphoedema – lymphatic drainage is impeded by benign or malignant tumours, or the lymph vessels were destroyed by injury, infection, tumour surgery or radiation treatments.

Often the lymphoedema is located on the shoulder or upper arm caused by a breast cancer surgery, in which the lymph nodes had to be removed in the armpit. In addition to the violations of the lymphatic vessels a lymphoedema can be caused by infection, inflammation or parasites.

© Woodhead Publishing Limited, 2011

In the case of massive interruption of the lymph drainage, body parts can sometimes increase dramatically. This disease pattern is known as elephantiasis. Usually a very time-consuming and sometimes life-long form of a complex physical decongestive is necessary.

The literature describes three stages of lymphoedema:

- *Stage 1* = reversible stadium, protein-rich oedema, only a few small, localised fibrosclerotic tissue alterations, oedema is still soft and reversible in high position
- *Stage 2* = spontaneous irreversible stage, fibrosclerotic changes and proliferation of the fat tissue, oedema is hard and not reversible in high position
- *Stage 3* = elephantiasis: extended fibrosclerotic changes, proliferation of the fat tissue, massive swelling.

A lymphoedema can also occur together with other diseases like fat redistribution. This combination is called lipoedema. A particularly complex case from a therapeutic point of view is a combination with chronic venous insufficiency. This disease pattern is called phlebo-lymphoedema (Partsch, 2002; Asmussen and Söllner, 2004).

22.2.3 Applications and textile materials for compression therapy

Application and parameters of compression therapy

Compression therapy, that is the use of external pressure on the human body, is the most established method and at the same time the most important additional treatment of venous and lymphatic diseases (Hohlbaum, 1987, 1988). It can be carried out additionally to other treatments or as a stand-alone therapy for a lifetime. Textile bindings/bandages, medical compression stockings or mechanical and pneumatic systems can be used for compression therapy. The effect of pressure exerted on the human body can be explained by the fact that liquids are not compressible. Because the tissue of the abdomen consists mostly of water and there is less space for the liquids to swerve within the tissue, the tissue pressure increases. In opposition to that, in the vascular system liquids are able to swerve, that is why medical pressure therapies have an ostensible effect upon the vascular system, where the tissues are high in liquid (Asmussen, 1991; Partsch, 2002, 2007; Brznak, 2003; Asmussen and Söllner, 2004).

Compression pressure

The compression pressure in a medical sense is the resulting pressure on the enclosed tissue and the embedded blood and lymphatic vessels. It can be generated by a means of compression from outside (compression stocking, bandage) or from inside through the muscle which expands against the resistance of the compression.

© Woodhead Publishing Limited, 2011

The compression pressure is normally stated as millimetres of a mercury column (mmHg). The value of the compression pressure for elastic textile materials can be determined according to the Laplace law (French mathematician, 1749–1827) with the following equation:

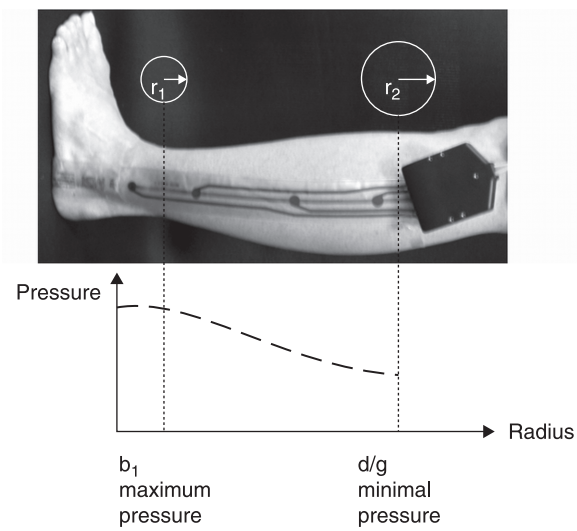
$$P = \frac{S}{R} \qquad [22.1]$$

where P is the compression pressure, S is the tension of the textile (in newtons per centimetre of bandage width), and R is the radius of the enclosed extremity. This means that the smaller the radius (with constant tension), the higher the pressure values become ($P \sim 1/R$). Figure 22.1 points out once again the relation between the pressure exerted to the leg through the compression bandage and the radius of the leg (Rabe and Pannier-Fischer, 2000; Thomas, 2002; Schuren and Mohr, 2008). The descriptions of the physical parameters in medicine (such as pressure and tension) differ from those used in engineering sciences. There is also no standard nomenclature known in literature.

Comparison between static pressure and operating pressure

In principle, there are two kinds of pressure with compression bandages: *static pressure* and *operating pressure* (Partsch, 2007). The particular value depends on:

- Type of bandage, especially the elasticity of the material
- The pre-stretching during application



22.1 Pressure flow on the human leg according to Laplace (Asmussen and Söllner, 2004).

© Woodhead Publishing Limited, 2011

- The strength of the bandage or stocking (for bandages the number of layers)
- The state of the bandage (age, number of wearing and washing cycles) (Partsch *et al*., 1999; Asmussen and Söllner, 2004; Partsch, 2007).

Static pressure is the permanent pressure a compression means exerts to tissue and vessels while the musculature is relaxed. The resulting power to apply or stretch a compression bandage is equal to the power which is affected to the tissue as static pressure. Therefore, static pressure is often described as the applied pressure. Normally, static pressure is constant (no shift, constant radius), so all pressure values of different compression classes (see the section 'Textile properties as the basis for compression material', on p. 488) are related to it. The static pressure influences mainly superficial vessels, which impedes their filling (Asmussen, 1991; Rabe and Pannier-Fischer 2000; Asmussen Söllner, 2004).

Operating pressure occurs when the muscle acts against the resistance of the compression means, because its volume increases through contraction. This way, the operating pressure is generated and is therefore described as muscle pressure. The operating pressure acts temporarily and compresses superficial and underlying vein and lymph paths. The efficiency of the muscle pump increases significantly through the high operating pressure because the veins can refill during the muscle's relaxation period and being pressed out again by the operating pressure. With an inelastic (short-stretch) bandage like a zinc-paste bandage (Unna's boot), the operating pressure values achieve their maximum (Asmussen, 1991; Rabe and Pannier-Fischer 2000; Asmussen Söllner, 2004).

Therapeutic pressure process

The compression should release continuously in the direction of the intended liquid transport, such as from distal to proximal for the leg. Table 22.1 shows recommended values for therapeutically normal pressure gradients on the leg. This pressure gradient is achieved by applying a compression bandage with constant elongation beginning from the ankle to the thigh (see Fig. 22.1 and Section 22.3.1). Because of the non-conical shape of the leg, the required

Table 22.1 Therapeutic pressure process

Measuring point	Relative pressure	
	Compression class II	Compression class III + IV
Above ankle measuring point b	100%	100%
Above ankle measuring point b1	70 to 100%	70 to 100%
Below knee joint measuring point c	50 to 80%	50 to 70%
Middle/end of thigh	20 to 50%	20 to 40%

© Woodhead Publishing Limited, 2011

continuous decrease in pressure needs to be created by means of padding materials. Pressure values can be comparatively high at bone margins because the bandage is more stretched at these points. Another aspect is the Laplace law (see Fig. 22.1). The radius at these areas is less compared to the other areas of the leg. So, high pressure values could be applied at bone margins at constant strain of the textile. Meanwhile, low or even no measurable pressure values could be registered at points like the perimalleolar areas (Bisgaard areas). To achieve a constant pressure distribution over the size of a leg's part, it is essential to pad the margins and fill other parts to achieve an almost cylindrical shape. Because of anatomy, a good pressure distribution especially on the feet is very difficult (Rabe and Pannier-Fischer, 2000; Asmussen Söllner, 2004; Partsch, 2007).

Examples for the effect of compression therapy to the human organism

- *Acceleration of venous flow*. The compression of extremities (e.g. the leg) with compression bandages, compression stockings or other means leads to the formation of a pressure gradient from the superficial tissue areas to the underlying areas. Tissue with a pressure lower than the compression mean pressure (skin, musculature, veins) is compressed from the surface decreasing to the inside. With an unchanged arterial inflow, the decrease of vein diameter leads to a 1.5-fold increase of venous flow rate (Strössenreuther, 1991). The effects of compression devices are used for bedridden patients. The decrease of flow rate, especially during the operative and post-operative period makes these patients susceptible to leg venous thrombosis. The acceleration of venous flow rate, supported by wearing compression stockings, helps to reduce the risk of thrombosis.
- *Functional improvement of the muscle pump*. The body rests on the sole of foot when standing and the vein plexus is pressed out. The venous valves of the feet are opened. The calf musculature is relaxed, and the venous valves in that area are closed. When the calf musculature is contracted, the venous valves of the feet are closed, the venous valves of ankles and calves open up. The change of exposure and release as well as opening and closing venous valves pump the venous blood actively to the heart. The pump mechanism is reduced if a venous valves hypofunction or dysfunction exists. The reduction of vein diameter by means of compression bandages allows the closing of the insufficient venous valves (Strössenreuther, 1991; Partsch, 2003). Another effect of compression therapy related to the muscle pump is the creation of a bearing, because the skin loses its ability to restore elasticity because of previous over-expansion. Thus, the efficiency of the reverse flow supporting muscle work increases.
- *Central haemodynamic effects*. The compression of extremities, especially the legs, leads to a significant relocation of liquids to central body parts. This increases the preload of the heart as well as the heart-time-volume. The

© Woodhead Publishing Limited, 2011

relocation of liquids, especially with shank and thigh bandages at the same time, should be paid attention to at marginal cardiac situations; it can overload an already damaged heart (Strössenreuther, 1991; Partsch, 2002).

- *Influence on arterial perfusion*. A compression bandage normally leads to a decrease of capillary perfusion in skin and muscles. It has been shown that after anti-oedema therapy of the affected leg with an inflexible permanent bandage the perfusion values increased significantly. The reduction of perfusion through leg compression is important for patients with arterial obstructive diseases. As stated in literature, any leg compression therapy is excluded with an ankle artery pressure below 80 mmHg. Completely inelastic bandages (zinc-paste bandages) with a contact pressure of only a few mmHg can amass an existing oedema with the help of the calf muscle pump. The perfusion can even increase here, while middle- or long-stretch bandages can force perfusion reductions. This is caused by higher static pressure values created from these bandages on the extremities (Rabe and Pannier-Fischer, 2000; Partsch, 2002). The effects described for the human organism are only a range of the total spectrum of compression therapy.

22.2.4 Textile compression materials: classification of means of compression

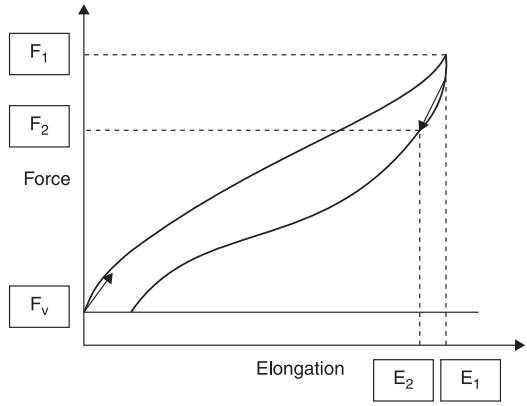
Textile properties as basis for compression materials

Compression therapy for the treatment of venous and lymphatic diseases uses several textiles as a means of compression, such as compression stockings or bandages for the exertion of external pressure to the human body. Depending on the therapeutic target, different compression materials are used. The classification and description of the properties considers several criteria (Partsch, 2007).

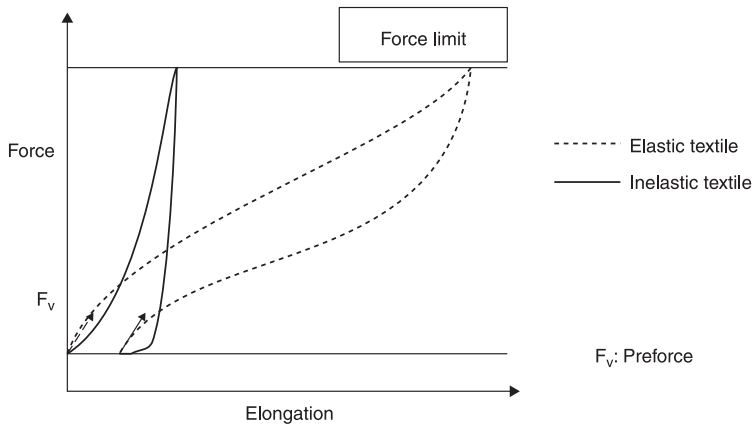
Force–elongation behaviour of textiles describes the relation between effective force and the resulting percentage elongation. The total elongation consists of reversible and persistent elongation, with moving transitions. Because of several possible types of load, different load tests can be executed. For elastic compression textiles accordingly to their application, the tensile force–elongation behaviour is decisive. During application, the textile structures are stretched (for bandages, related to the bandaging technique and state of musculature; for compression stockings, related to the elongation during pulling on). Afterwards, the material changes back into the elongation state during wearing and alternates between static and operating pressure according to the patient's movements (Fig. 22.2).

Tension elasticity can be described as 'the ability of a material to elongate under the impact of a tension force and to return to its original dimension all or part when released' (Reumann, 2000, p. 98) and indicates how fast or not a material fatigues in this process.

© Woodhead Publishing Limited, 2011



22.2 Force–elongation behaviour of a compression textile during application: (1) Pulling on; (2) wearing state.



22.3 Comparison of elastic and inelastic textiles in force–elongation behaviour (single tension load within constant force limits).

The creation of the desired force–elongation properties occurs in the interaction of material, fabric construction technology and finishing. Thread materials used for elastic bandages and compression stockings are structure-elastic high-twisted yarns, structure-elastic textured multifilaments and substance-elastic, raw or enwinded elastomers (Fig. 22.3).

Compression textiles: properties and applications

The *compression force* of a bandage or compression stocking is the restoring force which affects during the state of wearing elongation on the patient. The compression force is determined by the kind (chemical structure, texture, thread construction), number and yarn count (diameter) of elastic threads. The kind of

© Woodhead Publishing Limited, 2011

Table 22.2 Classification of bandages according to their elongation properties

Name	Maximal elasticity (%)
Inelastic bandages	0 (zinc-paste bandage)
Short-stretch bandages	to 60 (90)
Middle-stretch bandages	60 (90) to 140
Long-stretch bandages	> 140

the crimp (rectangular crossing of threads during weaving or mesh formation during knitting and warp knitting) also plays an important role.

The classification of compression stockings according to RAL-GZ 387 results from these force values (Asmussen, 1991; Partsch *et al*., 1999) (Table 22.2). The classification for compression bandages is more difficult because of the used bandaging techniques. In the British standard BS 7505:19956 six categories exist: type 1 describes light elastic retention bandages, type 2 supporting bandages (inelastic, short-stretch) and type 3A to 3D compression bandages. Those four classes are evaluated for their ability to exert a specific pressure value to a given ankle size (23 cm); the bandage is applied with a 50% overlap between two sequential layers.

The German standard classifies the compression bandages into four classes too, comparable with RAL-GZ 387. The limits between the British and German standards differ from each other. This could be lead back to differences of the required pressure values and the use of different testing procedures.

Elongation describes the increase of length of a compression textile during a defined load. Because this elongation is also known as 'stretch', terms like long-stretch/short-stretch bandages were created (Asmussen, 1991; Partsch *et al*., 1999; Asmussen and Söllner, 2004).

Short-stretch bandages have a low elongation and set a high resistance against the muscle's contraction. Therefore, they are characterised by a high operating pressure, which leads to a compression of the underlying veins too. In comparison to the high operating pressure short-stretch bandages have a low static pressure so that the vessels can refill during the state of rest (Rabe and Pannier-Fischer, 2000; Partsch, 2005). Because the body contours can only adapt on a small scale, an exact bandage technique and regular control of the bandage are necessary.

Long-stretch bandages avoid the contracted muscle through their high elongation ability. They are characterised by a low operating pressure, underlying veins are influenced less. The high restoring force exerts high pressure values to the body in the state of rest and compresses the peripheral vessels which impede the refill of the veins (von Gregory, 1978; Rabe and Pannier-Fischer, 2000).

The descriptive elongation (in per cent) of compression bandages is determined in a tension test with a tensile load of 10 N/cm of the bandage's width and as used

© Woodhead Publishing Limited, 2011

in praxis with the normal load of 3 N/cm of the bandage's width respectively (von Gregory, 1978; Weber *et al*., 1991).

The classification of compression bandages according to their elongation is listed in Table 22.2. Elastic compression stockings feature elasticity in both, longitudinal and cross-direction because of knitwear's structure. Elasticity in cross-direction plays an important role for the application of the stockings when pulling them with the lowest diameter (b-value) over the significantly bigger size of heel and instep (Asmussen and Söllner, 2004).

However, compression stockings are classified not according to their elongation but to the static pressure in the ankle area (similar to the compression classes). Another way of classification for compression textiles is the *duration of application* on the patient. Table 22.3 shows the main differences between removable and permanent bandages. The change-overs from maintenance to anti-oedema therapy are floating so that also the classifications change according to author and kind of therapy (Rabe and Pannier-Fischer, 2000; Partsch, 2002).

Table 22.4 shows the classification of compression bandages according to their *adhesive properties*. They can be differentiated into:

- Non-adhesive
- Cohesive
- Adhesive bandages.

Table 22.3 Classification of compression bandages for their application period

Name	Removable bandages	Permanent bandages
Period of application	Removed daily	Several days, up to 2 weeks
Compression means	Middle- or long-stretch bandages, compression stockings	Short-stretch bandages, adhesive bandages
Area of effect	Superficial vessels, tissue	Underlying vessels, tissue
Application at	Light to heavy swells	Heavy swells
User	Qualified staff or the patient	Qualified staff only

Table 22.4 Classification of bandages according to their adhesive properties

Name	Property
Non-adhesive	Non-adhesive, neither on skin, nor on other surfaces
Cohesive	Non-adhesive on other surfaces, only on the plies of the bandage
Adhesive	Self-adhesive on skin and other surfaces

© Woodhead Publishing Limited, 2011

They are used depending on the kind of therapy (Asmussen, 1991).

According to the clinical picture and goal of therapy, compression bandages or compression stockings can be applied. There is no standard technique for applying a *compression* (*phlebologic*) *bandage* and the following methods are used:

- Compression bandage with counter-packing technique
- Short-stretch bandages according to Sigg
- Cushion bandages
- Compression bandage with a long-stretch bandage
- Zinc-paste bandage, for highest pressure values; exact shaping of the bandage is essential
- Multilayer bandage (four-layer system, for English-speaking areas)
- Pütter bandage (Hach and Hach-Wunderle, 2000; Dissemond, 2005; Kammerlander, 2005; Partsch, 2007).

A *medical compression stocking* is an elastic textile with contact pressure in the ankle area (measuring point b) of at least 18 mmHg. Further classification depends on these contact pressure values (for Germany, as shown in Table 22.5). According to the goal of therapy either circular-knitted or flat-knitted stockings are used (Rabe and Gerlach, 2006).

Table 22.5 Compression classes for compression stockings

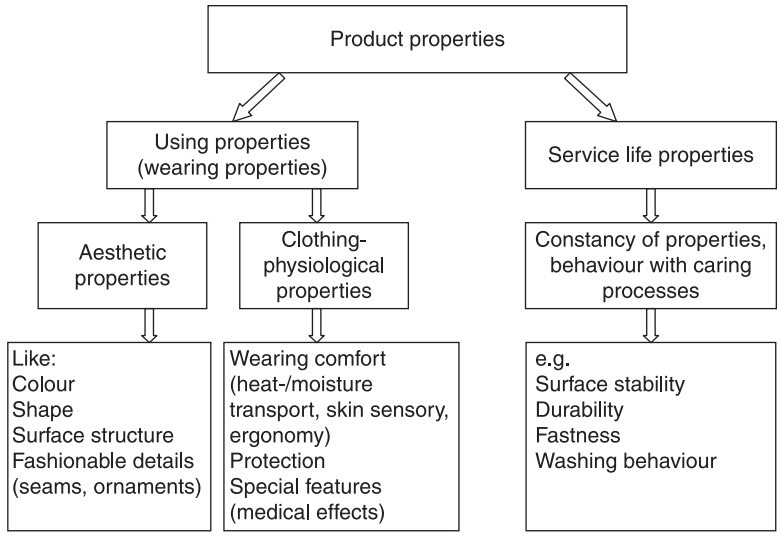
Characteristic	Class			
	I	II	III	IV
Compression intensity	Light	Medium	Strong	Very strong
Pressure near the ankle area (mmHg)	18–21	23–32	34–46	≥ 49

22.3 Improving patient acceptance of medical bandages and stockings

22.3.1 Essential product properties

In general, the trend in the textile industry leads to demanding, highly innovative products. This includes factors such as wearing comfort and wellness as well as performance effects (Hartmann and Ullsperger, 1999). Medical textiles such as bindings/bandages and medical compression stockings cannot hide from this trend. Especially during the last years, there have been continuous improvements in the properties of compression textiles. The goal here is better acceptance of the methods of treatment along with increasing success of therapy and the accompanying cost efficiency, as well as the sale of commercially available products.

© Woodhead Publishing Limited, 2011



22.4 Essential product properties (Kirstein, 2000).

Concerning the entirety of relevant product properties of textiles, a differentiation between wearing and service life properties is recommended. Most important for patient compliance here are wearing properties. The customer expects fashionable textiles with a high wearing comfort besides the medical functionalities (fig. 22.4).

'Wearing comfort' describes a generally neutral state without the appearance of inconvenience and pain. Wearing comfort is a combination of properties which make the usage as comfortable and adequate as possible under the following aspects (Hofer, 1997; Höfer, 2008):

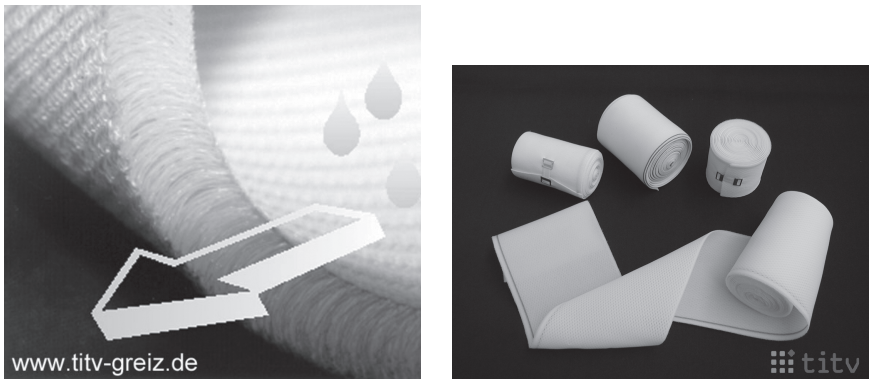
- Thermophysiological wearing comfort (heat and moisture exchange)
- Skin-sensory properties (tolerance, haptics, softness, less stiffness, etc.)
- Ergonomically wearing comfort (mobility, resulting stress on the body, correct fit)
- Health and performance support.

Some examples for an improved wearing comfort of compression textiles will be given subsequently.

22.3.2 An example for improvement of thermophysiological properties

The aspects of thermophysiological wearing comfort (heat and moisture exchange), skin-sensory properties (softness and less stiffness) and ergonomic

© Woodhead Publishing Limited, 2011



(a) (b)

22.5 Use of spacer fabrics for compression bandages; (a) spacer fabric structure with sweat and rapour transport (schematic), (b) 3D knitted compression bandage.

wearing comfort (patient mobility) were improved with the development of three-dimensional structures for short stretch bandages for lymph drainages.

The conventional bandaging technique uses a tube bandage, wadding or foam for support/padding and several short stretch bandages for compression. This multi-layer system leads to stiff or immobile extremities and trapped heat under the bandage. The TITV Greiz developed a three-dimensional short stretch bandage based on the double raschel technology (Wollina *et al*., 2003; Rotsch *et al*., 2009; Schwabe *et al*., 2009) (fig. 22.5). This three-dimensional knitted elastic compression bandage combines several advantages:

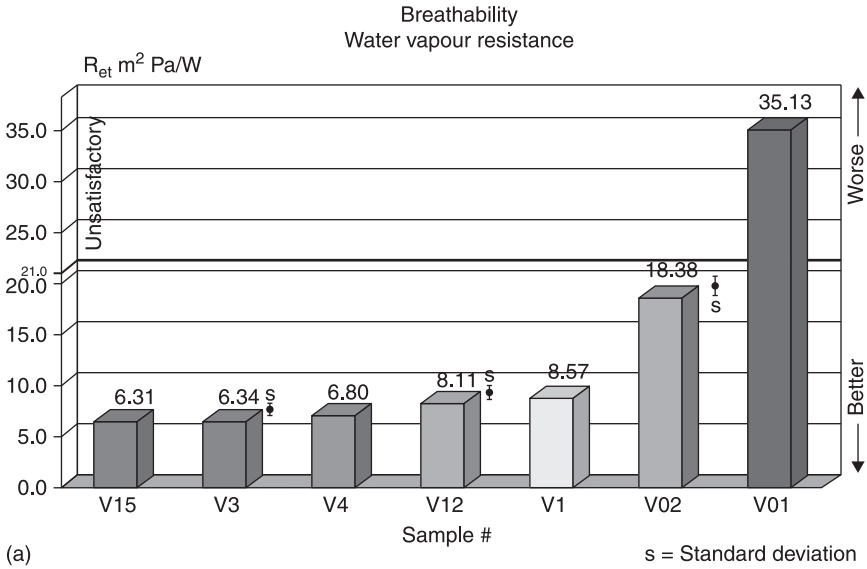
- Saving of supporting material
- Optimal physiological comfort
- Easy care (short drying cycles)
- Reusable
- Improved patient compliance.

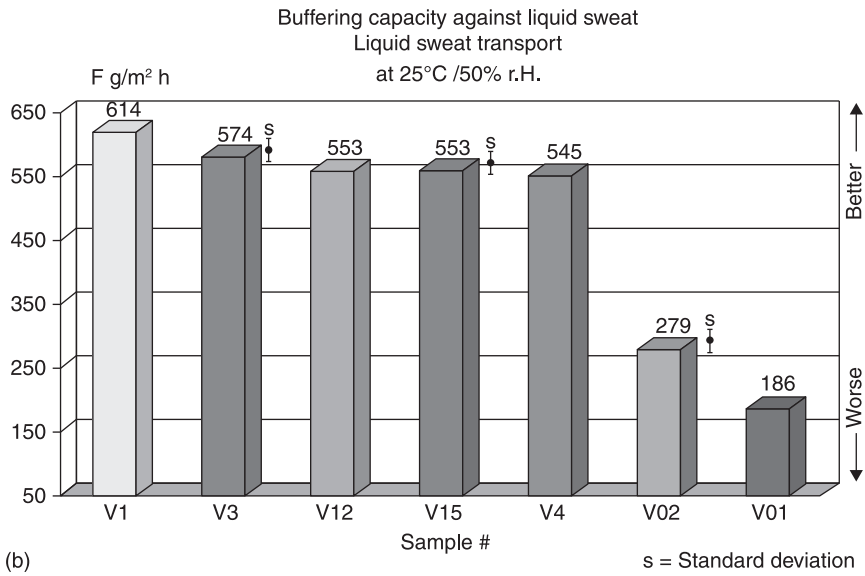
Besides the determination of the clothing–physiological properties of three-dimensional bandages in comparison to conventional bandages, the BPI Hohenstein ran a series with test persons in a climate chamber to verify their subjective feelings with the parameters tested. The result was good consent with the most important parameters (Heide and Möhring, 2005) (Fig. 22.6).

22.3.3 Future trends and possibilities in textile finishing

As already shown, even medical compression textiles cannot close to the trend of textiles. Besides the medical function, the customer expects fashionable textile constructions with as many additional features as possible. An example

© Woodhead Publishing Limited, 2011





22.6 Results of tests for clothing physiological properties in comparison to conventional bandages (Heide and Möring, 2005). (a) Breathability of spacer fabric bandages (V1–V15) in comparison to conventional bandage materials (V 02 and V 01) for CPE; (b) sweat transport of spacer fabric bandages in comparison to conventional bandage materials (V 02 and V 01) for CPE.

© Woodhead Publishing Limited, 2011

would be patterned compression stockings with a massage effect. Colours, partial colouration, perfect fit of the product and further additional features will assure wide acceptance (=compliance) in the future.

Possible additional properties of textiles realised through textile finishing can be caring or antimicrobial effects, as well as cooling, refreshing or wellness-increasing fragrances, a homogeneous tan and the protection from UV light.

These effects can be achieved through the integation of substances into systems with open structures, like cyclodextrines, dendrimeres, crown ethers or similar. A disadvantage with open systems is the complete loss of these features after a few washes. A compromise is the insertion of agents in an additional rinse cycle which could even consider customer preferences.

Exceptional positions have hollow filaments where selected agents can be absorbed into the fibres and released during their disintegration. Systems with closed structures have a more selective and stable effect. Capsule systems (micro- or nanocapsules and such with block copolymers) protect the enclosed substances during the production process and the storage of textiles and release those only during the textile's usage through specific reactions like friction or perspiration. However, after a maximum of 20 washes, most of the capsules are inoperative and need to be reloaded for a constant effect.

During the spinning process of chemical fibres it is possible to add additives which act as array components. Organic additives such as chlorinated biphenyls, natural terpenes, alga or others are examples. The effect of incorporated additives is similar to the textile's life cycle, because released silver ions could be replaced with particles from the inside the fibre array, for instance.

Also, direct linking of silver through binding systems or a nanostructure realised through technologies like sol–gel coating processes allow the bedding of substances as a thin metal oxide layer (e.g. silicon oxide) and their release over a long time period.

The release of agents from textiles is already approved for applications such as antimicrobial finishings for textiles (Hohlbaum, 1987, 1988; Klyscz *et al*., 1996; Hofer, 1997; Höfer, 2008; Kirstein, 2000; Lampe, *et al*., 2002; Kammerlander, 2005; Heide *et al*., 2006; Lansdown, 2006; Lai and Li-Tsang, 2009). For patients with neurodematitis an improvement of their health state by using silver-bearing textiles was proved (Heide *et al*., 2006).

Through the continuous release of small dose rates, the skin care of patients who wear compression stockings is significantly better than a single medication of larger amounts. This is more reasonable considering the skin of those patients is often in the pre-existing condition. Continuous wearing of compression stockings is an additional strain for the skin, and irritations can appear. Caring substances could be vitamin E, natural or synthetic vitamin C and herbal agents based on aloe vera, alga, maiden-hair tree or tea tree oil (Mathis, 2002; Zyschka, *et al*., 2004; Mathis and Mehling, 2006; Umbach, 2006).

© Woodhead Publishing Limited, 2011

22.3.4 Compression properties

Adaption relating to the patient: Customisation of compression textiles

The correct adaption of compression means to the individual patient's body geometry is an essential aspect of compression therapy for the accomplishment of a desired therapeutic success. Different methods can be used to realise the required pressure behaviour. At the beginning of a therapy, the accordant size and length dimensions (e.g. for the leg) are gathered with a measuring tape. A fitting compression stocking can now be selected with the collected data according to the size measurement table of a valid standard (e.g. RAL GZ 387) or can be manufactured individually for different geometries. This is possible within certain geometrical limits with freely programmable knitting machines.

Optical technologies also exist which will gather individual leg geometries in addition to the manual methods. Stocking manufacturers use several methods for digital recording together with image processing software and use the digital data of the leg's dimensions with the machine settings for individual customisation. This assures perfect adaptation to the accordant leg geometry of the patient.

According to the intended therapeutic effects of compression therapy, bandages can also be selected by considering their type and the bandage technology. The control of the applied compression pressure is difficult in these cases and needs practice as well as the therapist's experience. For patients, correct self-bandaging is a challenge. Simple visual aids include optical indicators on the bandage's surface. They make application easier, for example by forming an ellipse in the unstretched condition and a circle when optimally stretched. This method is also known for compression stockings (Thomas and Fram, 2003).

For optimal control of the applied pressure values at compression stockings and bandages, *in vivo* pressure monitoring with suitable systems is the best solution. A sensor system can record the pressure values and adapt them in comparison to the therapeutic targets through the change of the bandaging technology or pre-stretching. Not only the correct application or fitting of a means of compression can be monitored by pressure measuring systems, but also measurable control of therapy through a decrease in leg volume and the accompanying loss of the compression effect or possible ageing of the compression material is ascertainable.

Pressure measuring systems

Investigation and quantification of the pressure generated by compression means started during the second half of the twentieth century with Van der Molen who established the basis with his studies in 1955. Until that time, the resulting pressure values were based on evaluations or the anti-oedema therapy effects achieved. Different methods existed without a requirement to scientific exactness and there were also different interests for the efforts of measuring

© Woodhead Publishing Limited, 2011

compression pressure. On one side, the attending therapist needs the knowledge about the resulting pressure the appropriate pressure means can perform. And, the compression pressure measuring instruments are essential for quality control of the existing compression devices.

For example in Germany the agreement of the German Quality Label Community for Elastic Stockings (GZG) and the implementation of four compression categories required the determination of the compression values and therewith the development of suitable testing procedures, including their proof of practicability and reproducibility (Partsch *et al*., 1999; Rabe and Pannier-Fischer, 2000).

The determination of the compression pressure demanded knowledge about the force–elongation behaviour (Lampe *et al*., 2002) of the materials being used and the adaptation of these data to the size of the patient's leg. Those so-called indirect measuring methods can be only adapted provisory to compression bandages. Although different elongation indicators are used here, the resulting pressure values display only an approximation to the real pressure values. This is a result of the individual bandaging technique of the therapist and the resulting winding of the bandage. The recording of compression values directly between the bandage and the skin is the best method for several medical or textile–technical problems (Steinberg and Cooke, 1993; Klyscz *et al*., 1996; Häfner, 2000; Partsch *et al*., 2006).

Three ways of compression pressure determination exist:

- Direct *in vivo* method
- Indirect *in vitro* method
- Control of therapy success.

A common trend in medicine is the so-called 'evidenced based medicine'. This serves the quality control of therapy and delivers the efficiency statements which service providers require for the payment of the accordant therapy services. This is a typical trend for compression therapies too. The 'evidence based compression therapy', also demanded by the International Union of Phlebology (IUP), uses different methods for it (Partsch, 2003, 2004). An appraisal of randomised monitored studies which investigated therapy and therapy process of several vein and lymph diseases, took place. Also, suggestions for missing studies and methods for the proof of effectiveness were made. An important object of investigation is the resulting contact pressure of the compression means and the derivation of the respective therapy process to the compression pressure. The direct *in vivo* determination of the compression pressure or the chronological pressure profile is an important method for it (Partsch *et al*., 2006).

The basic principle of indirect *in vitro* methods is the determination of the force–elongation behaviour of the fabric or knitwear. Further mathematical calculations give the compression pressure on the accordant leg size (Häfner, 2000; Lampe *et al*., 2002). The compression pressure is the force necessary to expand the compression stocking according to the manufacturer's specifications.

© Woodhead Publishing Limited, 2011

The non-destructive measuring with a dynamometer is valid according to RAL-GZ 387 at the measuring points b, b1, c, d, e, f and g (Rabe and Pannier-Fischer, 2000).

Indirect *in vitro* measuring of compression pressure is well suited for the determination of the compression pressure and the comparison of medical compression stockings, their quality assurance and production. It should be kept in mind that the resulting pressure values are only valid for legs which correspond to the investigated elongations and leg sizes. The indirect methods are provisory suitable for multi-layer compression bandages. A single compression bandage can be characterised by their force–elongation chart but it is difficult to evaluate the friction of the windings among each other.

Amongst others, the following *indirect methods* are used:

- Hatra Pressure testing unit by Hatra, introduced 1972 in England
- Hosy-Method, by Weber and Göhr, developed in the 1980s in Hohenstein, Germany
- Pneumatic measuring, published by Stolk 1980 (Rabe and Pannier-Fischer, 2000; Asmussen and Söllner, 2004; Partsch, 2007).

The goal of *direct in vivo methods* is the measuring of compression pressure directly on the affected extremity. The problem here is that human extremities have no ideal cylindrical shape and the compression pressure is inversely proportional to the radius of the extremity. Thus, the compression pressure can only be determined on a limited and small area with a constant size. This means that the sensor itself influences the measuring values through its construction height. Therefore the results of these methods are only approximated values for defined areas of the leg. Elastic capsules are placed between the bandage and skin and inflated. This allows the determination of the back pressure of the means of compression at the point where the capsule's internal pressure is equal to the back pressure, and the compression material releases. This was first determined with simple manometers. Several pressure monitoring systems and electro-pneumatic tools followed later and allowed dynamic measuring on walking patients. From 1965, force-dependent resistance or piezo-resistive sensors were used more frequently. The requirements for sensors were and are still today:

- Negligible volume of the sensor for a constant leg size
- Easy handling of the system
- Simultaneous measuring at different measuring points.

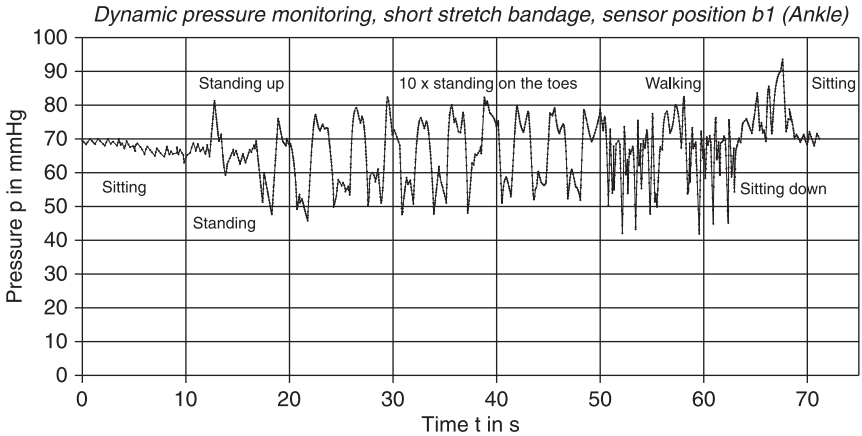
The following direct methods are used:

- Tonometer by van der Molen, introduced in 1955
- SIGG-Tester, introduced in 1964
- Measuring tool by Assum, introduced in 1965
- Komprimeter by Haid, introduced in 1965

© Woodhead Publishing Limited, 2011

- Medical Stocking Tester (MST), described in 1978 for the first time by Borgnis de Bruyne and Dvorak
- Talley system, introduced in 1993
- Contact pressure system MCDM 1 by Klyscz, introduced in 1996
- Contact pressure measuring system by Blazek and Schultz-Ehrenburg, introduced in 1997
- Novel-pliance pressure measuring system, available since the 1990s in different layouts
- Kikuhime pressure measuring system, developed at the end of the 1990s at the Technical College Hokkaido, Japan (Steinberg and Cooke 1993; Partsch *et al*., 1999; Häfner and Eichner, 2002; Rohrer and Rotsch, 2005; Lai and Li-Tsang, 2009).

Figure 22.7 shows an example of a dynamic pressure distribution during a defined sequence of movements of a test person. The difference between static and operating pressure can be clearly identified. This difference is an important criterion for evaluating the compression textiles. In phlebology, the term 'stiffness' has been introduced. This term may be understood as the stiffness or effectiveness of a compression textile. The static pressure should be minimal and the operating pressure should be much higher to ensure a filling of the vessels and an active pumping of blood in the upper body. The high pressure fluctuations also have a massaging effect on the surrounding tissue (Partsch, 2005a,b; Rotsch *et al*., 2005; Partsch, *et al*., 2006).



22.7 Example for dynamic pressure measurement of static and operating pressure (Rotsch *et al.,* 2005).

22.4 Conclusions

The development of medical compression textiles is process of the utmost complexity process. On one hand, the medical and therapeutic requirements like

© Woodhead Publishing Limited, 2011

the compression pressure and pressure distribution need to be realised or thermo-physiological properties need to be fulfilled by means of the textile technological processes. On the other hand, the individual adaptation of compression textiles considering modular bandaging systems, bandaging materials, patient-individual manufacturing or additional compression pressure measurements are of increasing importance. The common goal of all those different developments is an optimal adaptation of the compression textile to the individual therapeutic and anatomical indications.

In addition to these requirements for compression textiles, therapists have an increasing interest in the so-called 'evidence-based medicine', where the proof of concept for a therapy or a compression device is a central issue. This is an important aspect, not only for medical but also for health economics reasons, because, in the future, therapy methods will increasingly only be paid for by the health and care insurance provider after the proof of concept. A preferred method here is the compression pressure measurement too, in which more and more detailed information regarding the resulting pressure on the patient has been increasingly researched during the last years.

Besides the medical requirements, the increase in patient compliance is another important aspect too. Particularly in medical compression therapy patient cooperation and a lasting use of the compression devices are essential. A good wearing comfort, optical and design improvements support this aspect. Compression stockings for instance are offered in a wide range of colours. The integration of additional functionalities such as scents and skin care agents in textiles implemented with different technologies also enhances patient acceptance.

The development of compression textiles is a complex process which requires interdisciplinary cooperation between different engineering and medical departments to ensure that individual requests are adapted to provide a therapeutically effective product to the customer.

22.5 References

Asmussen P D (1991). Konstruktion von Kompressionsmitteln, Sortiment. In *Lehrbuch der Lymphologie für Mediziner und Physiotherapeuten. 2. bearbeitete Auflage*. Földi M and Kubik S (eds.). Gustav Fischer Verlag, Stuttgart, Jena, New York.

Asmussen P D (1991). Physikalische Grundlagen. In *Lehrbuch der Lymphologie für Mediziner und Physiotherapeuten. 2. bearbeitete Auflage*. Földi M and Kubik S (eds.). Gustav Fischer Verlag; Stuttgart, Jena, New York.

Asmussen P D and Söllner B (2004). *Kompressionstherapie – Prinzipien und Praxis, 1. Auflage*, Urban und Fischer, München, Jena.

Brznak, K-D (2003). Kompressionstherapie – Grundlagen, Wirkungen und Anwendungen. *Orthopädie-Technik*, 3, 194–201.

Dissemond J (2005). Kompressionstherapie bei Patienten mit Ulcus cruris venosum. *Deutsches Ärzteblatt*, 102 (41), A2788–A2792.

Hach W and Hach-Wunderle V (2000). Die Kompressionstherapie in der Chirurgie der primären Varikose. *Gefässchirurgie*, 6(1), 47–53.

© Woodhead Publishing Limited, 2011

Häfner H-M (2000). Tübinger Studienergebnisse zum Druckverhalten verschiedener Kompressionstherapeutika. *Orthopädie-Technik*, 12, 1059–1062.

Häfner H-M and Eichner M (2002). Klinische Überprüfung des Anpressdruckes unterschiedlicher Konfektionsgrößen des zirkulären Kompressionsfertigverbandes Tubulcus®. *Phlebologie 05*, 31, 108–111.

Hartmann W D and Ullsperger A (1999). Smart Clothes – wie intelligent wird unsere Bekleidung im nächsten Jahrtausend sein? In *Jahrbuch für die Bekleidungsindustrie*. Schierbaum W (ed.)., Schiele & Schön, Berlin, pp. 28–51.

Heide M and Möhring U (2005). Entwicklung wiederverwendbarer Abstandsgewirke mit definiertem dehnungselastischen Verhalten zur Abfallvermeidung bei der Komplexen Physikalischen Entstauungstherapie. Schlussbericht BMBF-Forschungsvorhaben Nr. 0330447, TITV Greiz.

Heide M, Möhring U, Hänsel R, Stoll M, Wollina U and Heinig, B (2006). Antimicrobial-finished textile three-dimensional structures. In *Biofunctional Textiles and the Skin. Current Problems in Dermatology*. Hipler U-C and Elsner P (eds.)., Karger, Basel, volume 33, pp. 179–199.

Hofer A (1997). Textil- und Modelexikon. Band 2, L – Z, Deutscher Fachverlag 7. Auflage.

Höfer D (2008). Die Zukunft der Medizintextilien – Hightech zum Wohle des Patienten. *Management & Krankenhaus*, 04 April 2008, p. 29.

Hohlbaum G G (1987). Zur Geschichte der Kompressionstherapie I. *Phlebologie und Proktologie*, 16, 241–255.

Hohlbaum G G (1988). Zur Geschichte der Kompressionstherapie II. *Phlebologie und Proktologie*, 17, 24–37.

Kammerlander G (2005). Grundlagen für eine Kompressionstherapie. In *Lokaltherapeutische Standards für chronische Hautwunden*, Springer Vienna, pp. 61–102.

Kirstein T (2000). Produktentwicklung für körpernahe Bekleidung unter Berücksichtigung der textilen Materialeigenschaften. Dissertation, Technische Universität Dresden.

Klyscz T, Rosenheimer M, Scherer W and Jünger M (1996). Dynamische In-vivo-Messungen des Anpressdruckes von Kompressionsstrümpfen mit einer Mikro-Sonde. *Biomed Technik*, 41, 69–73.

Lai CH and Li-Tsang CW (2009). Validation of the Pliance X System in measuring interface pressure generated by pressure garment. *Burns*, 35, 845–851.

Lampe R, Mitternacht J and Gradinger R (2002). Zugmessungen zur Ermittlung der Kompressionseigenschaften von Bandagen. *Orthopädie-Technik*, 9, 706–713.

Lansdown A B G (2006). Silver in health care: Antimicrobial effects and safety in use. In *Biofunctional Textiles and the Skin, Current Problems in Dermatology*. Hipler U-C and Elsner P (eds.). Karger, Basel, volume 33, pp. 17–34.

Li-Y (1997). Bekleidungskomfort und Fasereigenschaften. Konferenz-Einzelbericht: The 4th Asian Textile Conference, Taiwan.

Mathis R (2002). Textilien mit kosmetischen Substanzen. *Melliand Textilberichte*, 5, 339–340.

Mathis R and Mehling A (2006). A serious approach to wellbeing with textiles. Lecture 45th Dornbirn Man-made Fibres Congress, 20–22 September 2006.

Partsch H (ed.) (2004). Evidence based compression therapy. *VASA*, 34(Suppl. 63), 3–6.

Partsch H (2002). *Kompressionstherapie von venösen Beingeschwüren. Wie funktioniert sie?*, Édition Phlébologiques Francaises, volume 2, 04-06, pp. 137–144.

Partsch H (2003). Evidence based compression therapy – eine initiative der International Union of Phlebology (IUP). *Phlebo J*, 2.

© Woodhead Publishing Limited, 2011

Partsch H (2003). Zum Verständnis der Pathophysiologie der Kompression. EWMA Positionsdokument, Medical Education Partnership Ltd.

Partsch H (2005). Die phasengerechte Kompressionsbehandlung beim Ulcus cruris venosum. *Orthopädie-Technik*, 4, 238–245.

Partsch H (2005). The Static Stiffness Index: A Simple Method to Assess the Elastic Property of Compression Material In Vivo. *Dermatologic Surg*, 31(6), 625–630.

Partsch H (2007). Kompressionstherapie bei venösen Unterschenkelgeschwüren. In *Manual der Wundheilung*, pp. 171–178.

Partsch H, Clark M, Bassez S, Benigni J, Becker F, Blazek V, *et al*. (2006). Measurement of Lower Leg Compression In Vivo: Recommendations for the Performance of Measurements of Interface Pressure and Stiffness. *Dermatologic Surg*, 32(2), 224–233.

Partsch H, Rabe E and Stemmer R (1999). *Kompressionstherapie der Extremitäten*. Edition Phlebologiques Francaises, Paris, pp. 68–74.

Rabe E and Pannier-Fischer F (2000). Therapie der chronischen Venenkrankheiten. In: *Grundlagen der Phlebologie*. Rabe E (ed.). Einführung, Köln, pp. 68–87.

Rabe E and Gerlach H (eds.). (2006). *Praktische Phlebologie: Empfehlungen zur differenzierten Diagnostik und Therapie phlebologischer Krankheitsbilder*, volume 2, Georg Thieme Verlag.

RAL – GZ 387 (2000). Gütesicherung, Medizinische Kompressionsstrümpfe. Deutsches Institut für Gütesicherung und Kennzeichnung e. V., Ausgabe 09 (2000).

Reumann R-D (2000). *Prüfverfahren in der Textil- und Bekleidungstechnik*. Springer Verlag, Berlin, Heidelberg.

Rohrer C and Rotsch C (2005). Measurement of interface pressure using a simple transducer and date-logger. 6th European American Congress on Venous Diseases. 30th Annual Congress of the Czech Society of Phlebology, Prague, Czech Republic 26–28 May 2005.

Rotsch C, Hanus S, Schwabe D, Neudeck A, Zschenderlein D and Möhring, U (2009). Textile Solutions for Diagnostic and Therapeutic Applications. Proceedings International Conference, Latest Advances in High-Tech-Textiles and Textile-Based Materials; 80 years Department of Textiles, pp. 41–47; ISBN 9789081392426.

Rotsch C, Oschatz H, Möhring U and Rohrer C (2005). Objektiver Vergleich von Kompressionsdruckmesssystemen für die Kompressionstherapie. *Orthopädie-Technik*, 11, 789–793.

Schuren J, Mohr K (2008). The efficacy of Laplace's equation in calculating bandage pressure in venous leg ulcers. Wounds, 4(2), 38–47.

Schwabe D, Hanus S and Möhring, U (2009). Abstandsgewirke – die optimale Basis für medizinische Anwendungen. *Orthopädie-Technik*, 11, 764.

Spitzenverbände der Krankenkassen (2008) Bekanntmachung der Spitzenverbände der Krankenkassen über die Fortschreibung der Produktgruppe 05 "Bandagen" des Hilfsmittelverzeichnisses nach § 139 SGB V vom 2. Juni 2008

Steinberg; Cooke (1993). Design and evaluation of a device for measurement of interface pressure, *J Biomed Eng*, 15(6), 464–468.

Strössenreuther R. H. K (1991). Wirkungsweise der Kompressionstherapie, In *Lehrbuch der Lymphologie für Mediziner und Physiotherapeuten, 2. bearbeitete Auflage*. Földi M and Kubik S (eds.). Gustav Fischer Verlag, Stuttgart, Jena, New York.

Thomas S (2002). The use of the Laplace equation in the calculation of sub-bandage pressure, Surgical Materials Testing Laboratory, Princess of Wales Hospital, Bridgend, Wales, 05 (2002).

© Woodhead Publishing Limited, 2011

Thomas S and Fram P (2003). An evaluation of a new type of compression bandaging system, Surgical Materials Testing Laboratory, Princess of Wales Hospital, Bridgend, Wales. Available: http://www.worldwidewounds.com/2003/september/Thomas/New-Compression-Bandage.html, [last update 09/2003].

Umbach K H (1996). Bekleidungsphysiologische Aspekte bei der Entwicklung funktioneller Textilien, Tagungsband der 3. Dresdner Textiltagung, Dresden.

Umbach K H (2006). Wellness-textiles – what do we mean by that?, 45th Man-made Fibres Congress Dornbirn 20–22 September 2006.

von Gregory R (1978). Eigenschaften elastischer Binden, *Phlebologie und Proktologie*, 7, 171–182.

Weber M, Külter H and Wulfhorst B (1991). Textiltechnische Aspekte zu Kompressionsverbänden, *Band- und Flechtindustrie*, 1, 25–27.

Wollina U (2005). Spezielle Anforderungen der sensitive und Ekzemhaut an Textilien, Vortrag zum Workshop "Neurodermitikerkleidung" am 03. November 2005 Technische Akademie Hohenstein e.V.

Wollina U, Heide M, Müller-Litz W, Obenauf D and Ash J (2003). Functional Textiles in Prevention of Chronic Wounds, Wound Healing and Tissue Engineering, In *Textiles and the Skin, Current Problems in Dermatology*. Elsner P, Hatch K and Wigger-Alberti W (eds.). Karger, Basel, volume 31, pp. 82–97.

Wuppermann T (2002). Die chronisch venöse Insuffizienz, Internist, 2002 43: 16–26 Springer Verlag.

Zyschka R, Brückmann R, Kammerer B and Schreiber H (2004). Wellness-Finish mit Vitamin E, *Textilveredlung*, 7/8, 1–4.

© Woodhead Publishing Limited, 2011

23

Superabsorbents and their medical applications

G. BARTKOWIAK, Central Institute for Labour Protection – National Research Institute, Poland and I. FRYDRYCH, Central Institute for Labour Protection – National Research Institute, Poland and Technical University of Lodz, Poland

Abstract: This chapter defines superabsorbents, and describes the chemical structures, properties, and forms in which they appear on the market (powder, fibres or fibrous structures). Attention is paid to their applications for medical purposes, hygiene and medical textiles, as well as improvements in clothing comfort. The development of superabsorbents is followed by reviewing US patents. Results of our own measurements of nonwoven textile structures containing superabsorbents used for comfort improvement are presented, as well as the ergonomics tests on clothing produced using these materials. According to these experiments the superabsorbent content in different medical and health related areas, especially in tight clothing or underwear, for improving wearer's comfort seems to be justified.

Key words: superabsorbent materials (SAPs), hydrogels, Oasis fibres, liquid absorption and retention.

23.1 Introduction

Superabsorbents known as hydrogels are hydrophilic cross-linked polymers (superabsorbent polymers (SAPs)) that swell in water. Sometimes they are called intelligent gels, because 1 g of hydrogel can absorb even up to 1000 g of water (Glados and Maciejewski, 1998). Two basic groups of superabsorbents can be distinguished. The first are physical gels, called reversible gels. They have the three-dimensional space network, in which polymer chains are bonded by an electrostatic force, hydrogen bonds and hydrophobic interactions. These gels are unstable and can be transformed into polymer mixtures, e.g. gelatine and agar–agar. The second group are chemical gels, stable gels with the three-dimensional space network, in which polymer chains are permanently covalently bonded (Nałęcz, 2002).

The production of superabsorbents on the industrial scale was undertaken in the eighties of the last century. Initially, the superabsorbents were produced in the form of powder. Their basic applications were sanitary articles designed for the absorption of water solution and physiological liquids. They are mostly used as diapers for children and adults as well as feminine hygiene products, and other similar applications. Undoubtedly, in these applications, superabsorbent materials will replace traditional absorbent materials such as cloth, cotton, paper wadding, and cellulose fibres.

© Woodhead Publishing Limited, 2011

At the beginning of the 1990s, the range of application was extended onto the other commercial areas such as the manufacture of electro-energetic and telecommunication cables and hermetic wires, agriculture (retaining water in the soil), packages (liquid absorption on food plates) and transportation (monitoring the liquid escaping during the transportation), artificial snow for motion pictures and stage production, and filtration. The ability of polymer gels to undergo the reversible conformational vibration, when some particular environmental parameter is changed, such as temperature, pH, salt concentration, etc., can be used in the development of mini-actuators, which are characterised by a high power-to-power weight ratio and build compliance. They can be used, for example, for intelligent clothing (Solari, 1994). Besides powder, superabsorbents are also produced in the form of foil and foam. The latest achievements of technique are superabsorbent fibres. There are great prospects for development.

The application of SAPs in medical textiles has been hugely significant, as they have been revolutionary in the care and treatment of patients. This chapter describes the superabsorbents used for medicine, hygiene and familiar (comfort) purposes. Definitions of superabsorbents are given, as well as their chemical structures, properties, and forms in which they appear on the market (powder, fibres or fibrous structures). Additionally, much attention is paid to their application for medicinal purposes (contact lenses, systems for the administration of drugs, hybrid organs, reconstruction of human muscle cells and blood vessels), hygiene and medical textiles (dressings, baby diapers, incontinence, table sheats) as well as for improvements in clothing comfort (in the tight clothing, underwear or half-masks). The direction of SAP development is followed on the basis of review of the US patents. Results of own measurements of nonwoven textile structures with the SAP content used for comfort improvement are presented as well as the ergonomic tests of parts of clothing produced by using these materials. According to these experiments the SAP content in different medical and health related areas, especially in tight clothing or underwear, the improvements in wearer comfort seem to justify the incorporation of SAPs.

23.2 Methods of obtaining superabsorbent polymers and their chemical structure

Superabsorbent polymers (hydrogels) are most frequently obtained as a result of the copolymerisation of vinyl and divinyl monomers in the presence of redox initiators. The monomers of basic significance are acrylamide, acrylic acid, methacrylic acid and their derivatives. The most frequently applied divinyl monomer is *N*,*N*-methylene-bisacrylamide (NMBA); less frequently, ethylene glycol diacrylate, sodium divinyl benzene sulfonate, tetrahydroxy methyl acethylene urea or allyl acrylate. Poly(ethylene glycol), poly(aspartic acid), poly(vinyl alcohol), maleic anhydride copolymers and poly(*N*-vinyl pyrrolidone)

© Woodhead Publishing Limited, 2011

are also used for the polysynthesis of superabsorbents (Bereś and Kałędkowska, 1992, Glados and Maciejewski, 1998).

The process of polymerisation usually occurs in the presence of initiators of polymerisation, the temperature or high energy radiation. Chemical and radiation methods of obtaining hydrogels are distinguished (El Fray, 2005).

In chemical methods persulfates are applied as the polymerisation initiators. Chemically cross-linked hydrogels are made as the result of polymerisation of monomers or the cross-linking of polymers. Hydrogels are obtained in the process of copolymerisation of hydrophilic monofunctional monomers with bi- or multifunctional ones, while acrylamide, acrylic acid and methacrylic acid are used. In this method such polymers as poly(vinyl alcohol) (PVAL), poly(ethylene oxide) (PEO), poly(*N*-vinyl pyrrolidone) (PVP), poly(acrylamide) (PAA) are applied (Roweton *et al*., 1997).

The radiation cross-linking of hydrogels lies in linking polymer chains by means of permanent covalent bonds, which, unless the whole macromolecule is destroyed, are not subjected to decomposition. The cross-linking process is initiated with gamma radiation emitted by cobalt-60 or caesium-137 and also the accelerated electron stream. In the above method gels are obtained by the cross-linking of such polymers as: poly(vinyl alcohol), poly(ethylene oxide), poly(*N*-vinyl pyrrolidone), poly(acrylic acid) (Bereś and Kałędkowska, 1992; Nałęcz, 2002).

Under the action of radiation on aqueous polymer solutions on the polymer chain the radicals are formed by the hemolytic breaking of C–H bonds. Additionally, as a result of radiolysis of water molecules, hydroxyl radicals are formed that can attack polymer chains, thus generating macroradicals. Such macroradicals contribute to the formation of covalence bonds on the chain and making the finally cross-linked structure of the system (Bereś and Kałędkowska, 1992; Nałęcz, 2002).

Poly(vinyl alcohol), poly(ethylene glycol), poly(acrylic acid) hydrogels are obtained by this method, as well as thermosensitive hydrogels obtained by the irradiation of aqueous solutions of poly(vinylmethyl ether.)

Properties of the formed gels, especially their swelling and permeability, depend on the polymer concentration and a dose of radiation. The cross-linking density increases proportionately to the increase of polymer concentration and radiation dose (Bereś and Kałędkowska, 1992; El Fray, 2005; Nałęcz, 2002).

Physical properties of superabsorbents depend on numerous factors such as the type of polymer matrix, functional group character, degree of polymer cross-linking, ratio of reactants, quantity of initiator, reaction temperature, degree of the comminution of product, chemical composition and temperature of absorbed solution among others (Glados and Maciejewski, 1998).

Small amounts of cross-linkers play a major role in modifying the properties of superabsorbent polymers. In addition to modifying the swelling and mechanical properties, the cross-linker affects the amount of soluble polymer found during the polymerisation as a result of its relative reactivity with acrylic acid or sodium

© Woodhead Publishing Limited, 2011

acrylate. Efficiency of cross-linking will also depend on the steric hindrance and reduced mobility at the site of pendant double bonds, the tendency of a given cross-linker to undergo intermolecular addition reactions, and the solubility of cross-linker in the monomer mixture.

The mechanism of swelling of ionised, cross-linked polymer networks is based upon the concept of osmotic pressure. According to Flory (1953), the polymer acts as a semipermeable membrane, which does not allow charge substituents to exit the polymer into the surrounding solution. This is because the ionised monomeric units contain fixed charges, which attract and fix ions from the outer solution. Therefore, a charge gradient is set up, in which the concentration of free ions is greater outside of the polymer. That is why the osmotic pressure exerted by the gradient causes the polymer chain to swell as further ions diffuse in.

If the superabsorbent polymer is more highly cross-linked, it is more rigid in the swollen state. Improving the rigidity of the particles enables the swelling particles actually to push aside the fibre component of the composite, thereby maintaining the porosity and permeability during subsequent contacts with liquid. However, this must be optimised, as particles which are too rigid will cause leaks by tearing the surrounding fibre.

The most efficient water absorbers are polymer networks that carry dissociated ionic functional groups. Except for the molecular-sized chains that make up the network, this picture of a network is remarkably similar looking to the mass of cotton fibres. The difference is that cotton takes up water by convection; water is 'sucked' up, wetting the dry fibres; SAPs work by diffusion on the molecular level, since their 'fibres' are actually long-chain molecules.

Water diffuses into a particle of superabsorbent polymer when the concentration of water is initially lower in the interior of the particle. As water travels into a particle, it swells to accommodate the additional molecules. Because the polymer molecules are cross-linked, they do not dissolve in the absorbing liquid.

The substrates used most often and the methods of obtaining from them the SAPs with the greatest significance and application in medicine are described in the next sections (Tyliszczak and Pielichowski, 2007). *Acrylic acid* is characterised by the strong chemical reactivity. Hydrogels are obtained by the homopolymerisation of acrylic acid or its copolymerisation with acryloamide. *N*,*N*'-methylene-bisacrylamide (NMBA), sodium divinyl benzene sulfonate, ethylene glycol diacrylate, glycol acrylate and other divinyl or acrylic compounds are used in the cross-linking of acrylic superabsorbents. Acrylic hydrogels are used as, among others, active dressings, the matrices in the systems for the controlled-rate release of active substances and in tissue engineering (Glados and Maciejewski, 1998; Tyliszczak and Pielichowski, 2007).

Methacrylic acid hydrogels are obtained as a result of methacrylic acid copolymerisation with acrylamide and their use in pharmacy and medicine includes controlled-rate release of active substance matrices. 2-Hydroxyethyl methacrylate (HEMA), a derivative of methacrylic acid, is used in the production

© Woodhead Publishing Limited, 2011

of contact lenses (Glados and Maciejewski, 1998; Tyliszczak and Pielichowski, 2007).

Poly(aspartic acid) (PKA) is a water soluble and hygroscopic compound, and due to such properties as non-toxicity and biodegradability is applied as a biomaterial, e.g. PKA complexes used in oncology. PKA-based hydrogels are obtained as a result of chemical or radiation cross-linking. Chemical cross-linking is carried out in polar solvents with the use of such compounds as polyamines, polythiols and amino acids (lysine, cysteine). The chemical cross-linking process can be carried out by a conventional method or by microwave radiation (Polaczek *et al*., 2003).

Poly(N-vinyl pyrrolidone) (PVP) is used in the production of hydrogels, which are obtained in the course of cross-linking of poly(*N*-vinyl pyrrolidone) with divinyl ethers of diethylene glycol. Hydrogels obtained in this way have been applied as dressing materials and systems for the controlled-rate release of active substances among others things (Glados and Maciejewski, 1998).

Poly(vinyl alcohol) (PVAL) based hydrogels are obtained as a result of the free-radical or radiation cross-linking of hydroxyl groups. Glutaraldehyde or 1,4-hexamethylene diisocyanate are applied as cross-linking agents. The obtained hydrogels are used in the production of membranes, active dressings, implants and systems for the controlled-rate release of active substances (Glados and Maciejewski, 1998).

Poly(ethylene glycol) (PEG) is applied in biomedicine, pharmacy, cell engineering and the production of hydro-gels due to such properties as biocompatibility and non-toxicity. Superabsorbents based on PEG are obtained as a result of free radical or radiation cross-linking of the end-hydroxyl group, as well as the result of copolymerisation with other chemical compounds. Triisoamines, polyfunctional isocyanates and diisocyanates and triol mixtures are used as cross-linking agents (Glados and Maciejewski, 1998).

Polysaccharides can be obtained by their chemical modification that consists of: gelation, grafting of an adequate monomer, hydrolysis and drying polymeric hydro-gels. Acrylonitrile, acrylamide and acrylic acid are the most frequently applied as grafting monomers. In this case, cross-linking takes place during the hydrolysis. Another cross-linking method lies in adding *N*-hydroxy-methylene-acrylamide to starch solution. Polysaccharide hydrogels are applied in the napkins production and in tissue engineering or as active dressings (Glados and Maciejewski, 1998).

Maleic anhydride is a strong electron acceptor and easily undergoes a radical copolymerisation, alternately with donor monomers such as alkenes and vinyl ethers. The reaction can be most favourably conducted in benzene, in which the nascent polymer is not soluble and precipitates as a white powder. A maleic anhydride ring can be easily opened, although at least one group remains unsubstituted. The other one can be easily a subject of the reaction of esterification or amidation. It is exactly because of this property that maleic anhydride copolymers can be easily cross-linked with other compounds. The most frequently

© Woodhead Publishing Limited, 2011

applied cross-linking agents are glycols, oxethylated glycerine and saccharides. Due to the use of maleic anhydride the amphiphatic gels can be obtained, in which the comonomer is acrylamide and α-olefines with long aliphatic chains. Those substances could be used as drug carriers, for use in the renal drug delivery (Glados and Maciejewski, 1998).

23.3 Forms of superabsorbents and their properties

23.3.1 Introduction

The desirable absorbent properties are the ability to absorb water, high velocity of reversible fluid absorption, high capacity of absorption, good mechanical strength, non-toxicity, chemical and heat resistance, and flexibility (Glados and Maciejewski, 1998). As mentioned previously, hydrogels are built of polymer chains linked in selected points, due to which they form a three-dimensional cross-linked structure. In the dry state, polymer chains have the form of tightly folded coils. The functional groups that are present in chains undergo solvation and dissociate under the influence of water. Positive ions detach and negative charges bonded to polymer chain repel themselves under the influence of electrostatic forces. This leads to a certain loosening of the polymer coil, which thus gains the possibility of further absorbing liquid, and finally forms a gel. The process ends when the particular polymer chains that form a spatial network have extended to maximum (Glados and Maciejewski, 1998).

The absorption of superabsorbents, also called swelling, is the most often expressed as grams of solution or water taken up by 1 g of dry gel. It can amount from a few to a few hundred grams solute per gram of superabsorbent and depends on many factors. The type of functional groups and the degree of polymer cross-linking have a decisive influence on this phenomenon. Another important limiting factor is a degree of the product comminution as well as the composition of absorbed solution. The presence of electrolytes and chemical compounds capable of reacting with the gel functional groups usually decreases the absorption of superabsorbents (Szlezyngier, 2000).

The ability to absorb water depends on the presence of ions in water, being 500 times of its weight (30–60 times its volume) for distilled/deionised water, but only 50 times of its weight for a 0.9% saline solution. The total absorbency and swelling capacity are controlled by the type and degree of cross-linking in the polymer. A lower density cross-linked polymer has a higher absorbent capacity and a softer and more cohesive gel can be formed from it. High cross-link density polymers exhibit the lower absorbent capacity than the low density cross-linked polymer and the gel strength is firmer, maintaining its shape under the low pressure.

Swelling is a diffusion phenomenon controlled by the affinity of swelling material molecules to the molecules of fluid. The swelling equilibrium of ionic gel is determined by the balance of three main forces:

© Woodhead Publishing Limited, 2011

- *Force 1*: free energy of the mixture of network chains and solvent
- *Force 2*: osmotic pressure inside the network resulting from the mobility of counter ions surrounded by the groups of permanent charges (ion swelling pressure)
- *Force 3*: flexible network response (flexible swelling pressure).

Forces 1 and 2 favour swelling of gel, in contrast to force 3 (Kiatkamjornwong and Punchareon, 1999).

When choosing the appropriate superabsorbent for an absorbing structure the following basic parameters need to be considered:

- *Absorption*: the ability to absorb the determined amount of liquid in the particular situation, when there is no loading on the fabric or fabric assembly. In some cases it is termed 'free absorption'.
- *Absorption under pressure*: the ability to absorb the determined amount of liquid in the situation, when there is a loaded fabric or fabric assembly. In the majority of cases the superabsorbent producers give the value of absorption at the following pressure values: 0.3; 0.5; 0.6 and 0.7 psi (where 1 psi = 6896 Pa).
- *Absorption of salt water*: due to the differences in the retention of distilled water and a liquid with even small amount of salt retention it is determined as the salt water absorption. Salt concentrations are 0.2–0.9% of NaCl.
- *Water retention*: an ability to keep the determined amount of water.

Superabsorbents can occur in different forms (e.g. powders, fibres). Superabsorbent powders as well as fibres differ in their properties.

23.3.2 Superabsorbents in the granulate and powder form

The most commonly available superabsorbent polymers are hard, dry, granular powders that look much like clean white sand or granular table sugar. The examples of typical superabsorbents in the granulate and powder form are presented below. Table 23.1 presents specifications for a superabsorbent used for sanitary napkins and baby diapers.

Product T5066 of the Degussa firm has the consistency of powder. Chemically, it is a sodium salt cross-linking polyacrylic. In combination with water it creates a gel stopping further liquid transportation (flow). This product is mainly used for technical applications (Degussa data sheet, 2010). The technical characteristics are:

- Granulation, 0–63 $\times 10^{-6}$ m
- Percentage of molecules (particles) of dimensions, 63 $\times 10^{-6}$ m, max 2%
- Size of molecules (particles) in the non-wetted state, minimum of 2 $\times 10^{-3}$ m
- Humidity of the traded product, 5 ± 2%
- Degradation temperature, above 200°C.

© Woodhead Publishing Limited, 2011

Table 23.1 Specification of superabsorbent used for hygiene products

SAP Powder Technical Data	
Appearance	White granules
Absorption capacity (g/g) (tea bag capacity, 10 min)	≥49
Moisture content (%)	≤4
pH	6.5–7.1
Bulk density (g/cm3)	0.59–0.69
Particle size distribution, on 850 μm (%)	≤1

Recently, innovative bio-based superabsorbents, made from renewable resources have appeared on the market. These products are not only an environmentally sustainable alternative to petroleum-based materials, but also offer an effective absorbency and moisture retention for baby diapering, adult incontinence, feminine hygiene, food packaging and other industrial applications. Examples of the newest generation of bio-based material are BioSAP™, Lysorb™ 218 and Lysorb™ 220 produced by the Archer Daniels Midland Company (ADM). ADM produces bio-based superabsorbent polymers for disposable personal hygiene applications (ADM, 2010).

23.3.3 Superabsorbents in the fibre form

Lately, synthetic absorbents in the fibre form have appeared on the market. Chemically they are cross-linked acrylic copolymers neutralised by a sodium salt. Application of sorbents of the fibre form solves the problem of their introduction into textiles. Table 23.2 presents information regarding superabsorptive fibres; and Table 23.3 lists their basic parameters (according to the producers' information). On the basis of data from Table 23.3 it can be stated that the fibres with the highest water absorption are: Fibredi and Fibresorb from Camelot. Fibres Fibredi are destined for the production of nonwovens by the paper technique.

Comparing the free sorption of salt water, which is important due to the application in pads absorbing sweat and materials absorbing human liquids, there is an insignificant difference between the fibres Fibresorb, Lanseal and Oasis. They absorb salt water to a similar degree; nevertheless, the salt water absorption under pressure is the highest for Oasis fibres. It is also worth noting that Oasis

Table 23.2 Superabsorptive fibres in the world

Producer	Country	Name of product
Camelot Superabsorbents Ltd	Canada	Fiberdri, Fibersorb
Technical Absorbents Ltd	UK	Oasis
Toyobo Ltd	Japan	Lanseal

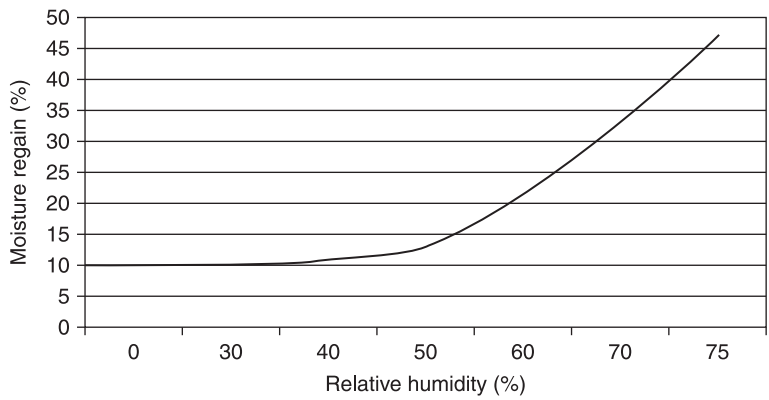
Source: Ackers, 1997

© Woodhead Publishing Limited, 2011

Table 23.3 Properties of superabsorbtive fibres

Type	Fiberdi		Fibersorb	Lanseal		Oasis
	1130	1160	908	5d	2.6d	101/2
Sorptive properties						
Distilled water						
Absorption (g/g)	280	350	380	150	120	80
Retention (0.5 psi) g/g	225	250	240	—	—	60
Salt water (0.9% NaCl)						
Absorption g/g	60	80	55	50	40	40
Retention (0.5 psi) g/g	47	60	35	20	15	30
Absorption under the load (0.3 psi) g/g	18	15	9	—	—	23
Rate of absorption g/g/s	1.2	0.8	1.0	70% of absorptive volume in time of 30s		90% of absorptive volume in time of 15 s
Strength						
Tenacity (cN/dtex)	—	—	1.0	1.9	2.4	0.4
Strain (%)	—	—	<15	15–25	25–35	22
pH	6.0	6.0	6.0	7.0	7.0	5.8

Note: 1 psi = 6895 Pa.

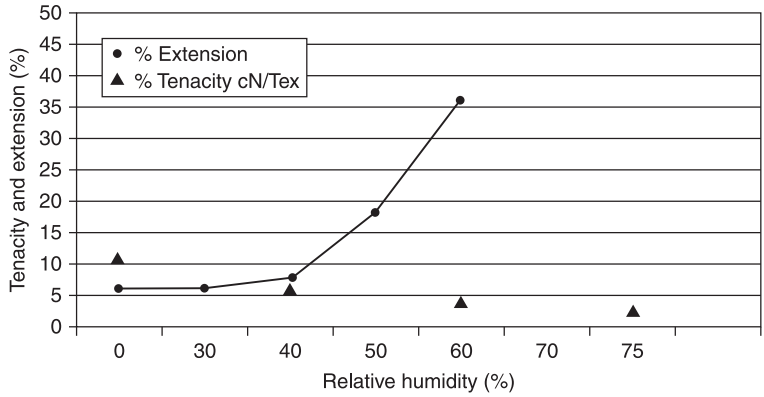


23.1 Water vapour absorption capacity of Oasis fibres dependent on the air relative humidity (according to the producer's data).

fibres are characterised by the highest absorption rate (about 2.4 g/g s for Oasis and 1 g/g s for the other fibres).

From the point of view of water vapour absorption superabsorbent fibres are better than powders. The ability of Oasis fibres to absorb water vapour (based on the producer's information) is presented in Fig. 23.1. (Other producers do not present such data.)

© Woodhead Publishing Limited, 2011



23.2 Oasis fibre tenacity and strength as a function of the air relative humidity (according to the producer's data).

With regard to strength, Lanseal fibres are superior; therefore, they have a very good spinnability. With the increase of air relative humidity, the strength of superabsorbent fibre decreases, but its strain increases. This relationship is presented in Fig. 23.2.

Based on an analysis of fibre properties, especially the absorption of salt water under pressure or not (Table 23.4), and the absorption of water vapour during periods of high relative humidity (RH) (Fig. 23.1), Oasis fibres should be appropriate for sweat absorptive pads for use under tight protective clothing to improve user comfort. Their other advantage is a high absorption rate (time of the total absorption is 15 s).

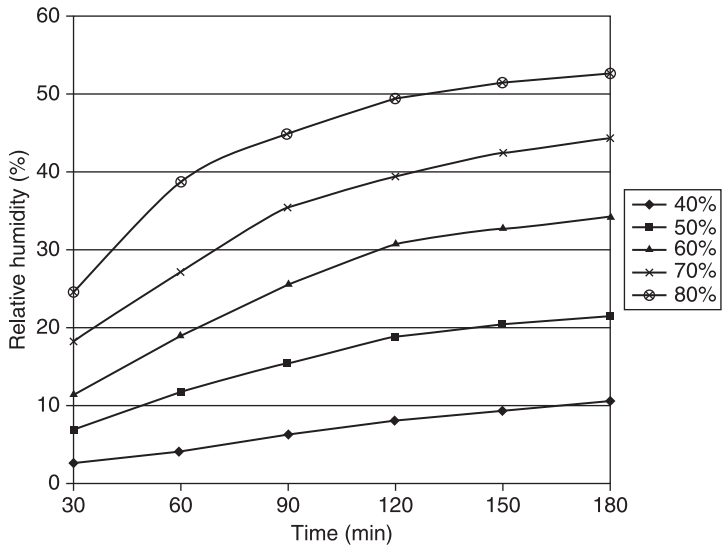
Table 23.4 Properties of Oasis type 102 fibres

Parameter	Value
Length (mm)	52
Tenacity at 40% RH (cN/tex)	
pH	5.8
Humidity (%)	15
Distilled water	
Absorption under the load (g/g)	45
Retention (g/g)	65
Free water absorption (g/g)	85
Salt water	
Absorption under the load (g/g)	21
Retention (g/g)	35
Free absorption after 15 s (g/g)	45
Free absorption after 20 s (g/g)	42

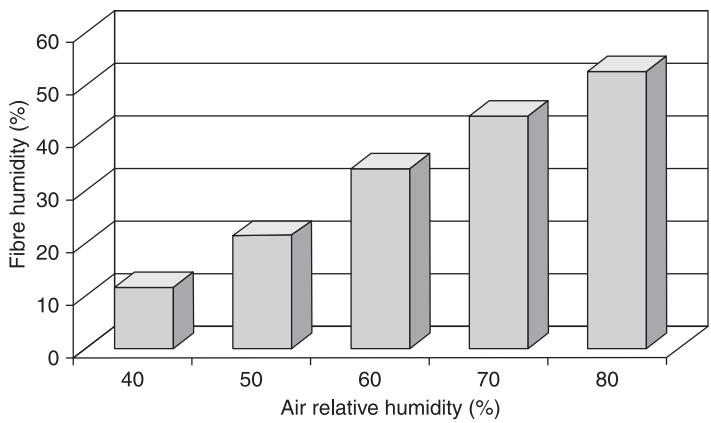
© Woodhead Publishing Limited, 2011

Properties of Oasis 102 fibres, as measured at the Central Institute for Labour Protection

The absorption of water vapour by the Oasis 102 fibres has been measured at the Central Institute for Labour Protection–National Research Institute (CIOP-PIB), Poland. Figure 23.3 presents the changes in time of fibre humidity at different air RH; while Fig. 23.4 shows the humidity of Oasis fibres after 180 minutes of being in air of different RHs.



23.3 Changes in the Oasis 102 fibre moisture over time in different air relative humidity (own research).



23.4 Moisture content of Oasis 102 fibre in different air relative humidity (own source).

© Woodhead Publishing Limited, 2011

The results presented showed that the Oasis fibres have a very good water vapour sorption over a wide range of air RH. After 30 minutes exposure in air of 80% RH they absorb about 25% of water vapour. This property is very important for their further application (for example, under non-permeable (tight) clothing, when the microclimate humidity after several minutes of work can achieve even 100%). The absorption of salt water by the Oasis 102 fibres was also determined in the CIOP-PIB laboratory. The results of such measurements are presented in Table 23.5.

Table 23.5 Free absorption of salt water (0.9% NaCl) by the Oasis fibre (g/g) on the basis CIOP-PIB measurements

Time	Absorption
After 15 s	20
After 30 s	25

23.4 Development stages of superabsorbent materials according to appropriate patents

This chapter also presents, in chronological order, the chosen inventions concerning the fibrous superabsorbents. Studying them can facilitate readers' understanding of the direction of development of textile superabsorbents applied mostly to sanitary and medical articles.

- *US Patent 3670069* – Process for forming hydroxyethyl cellulose fibres having the high water absorption and high water retention properties (Mitchell *et al*., 1972).

Fibrous cellulose products are prepared by extruding cellulose solutions by a special fibre forming device, which comprises porous extrusion media containing a controlled number and distribution of discrete flow paths. The cellulose fibres prepared in this way exhibit unique and highly desirable physical and structural characteristics for use in forming new and improved nonwoven fabrics and disposables.

- *US Patent 3940542* – Polyurethane hydrogel fibres and tapes and composites with natural and other synthetic fibres or films (Knopf *et al*., 1976).

According to this patent, water swellable, lightly cross-linked hydrogel polymer fibres, tapes and ribbons are produced by extruding or spinning a solution of an isocyanato terminated prepolymer comprising the reaction product of a poly (alkyleneoxy) polynol having an average molecular weight up to about 25 000 and an organic diisocyanate into a coagulant bath; whereby the prepolymer is lightly cross-linked by a cross-linking agent, which is either water or an organic polyamine. The cross-linking agent is present in the coagulant bath at a very dilute concentration.

© Woodhead Publishing Limited, 2011

The hydrogel fibres produced by this invention have several advantages over the previously produced powders and granular particles. They can be accurately placed in woven and nonwoven articles, when combined with other fibres and they remain in place during handling and even after swelling during the use. The water absorbency of the finished article can be controlled or regulated by selecting the reactants and their relative proportions in producing the isocyanato terminated prepolymer used to manufacture the hydrogel fibre and by regulating the amount of hydrogel fibre used in making the composite. An advantage is their ability to produce a hydrogel fibre of any desired length or linear density. Furthermore, the produced polyurethane hydrogel fibres possess a high absorption capacity for salt solutions in addition to their high capacity for water. The fibres are insoluble in trichloroethylene solvent and have the properties given in Table 23.6. The fibres can be used in diapers, bed pads, facial tissues, towels.

- *US Patent 4721647* – Absorbent article (Nakanishi *et al*., 1988).

An absorbent article comprises a base material of fibres, a part or all of which are hydrophobic and water-absorbent polymers, a part of which is in the form of substantially spherical particles and has been bonded to said fibres to surround them. Fixation of the polymer is secured. The softness of basic material is maintained. The invented article is suitably usable in sanitary and medical articles such as sanitary napkins, disposable diapers, and bandages as well as the other areas of economy like agriculture, forestry, civil engineering.

- *US Patent 5002814* – Superabsorbent fibre flocks, methods for their production and application (Knack and Beckert, 1991).

The invention relates to superabsorbent fibre flocks comprising a core of absorptive polymer, wherein short polymer fibres have been embedded. Such superabsorbent fibre flocks can be produced by binding absorbent polymer particles to each other and to the polymer fibres with the aid of a bonding agent and by gridding the fibre flocks, thus obtained to the required particulate size. Such superabsorbent fibre flocks can be used in sanitary products, especially in baby diapers, menstrual pads, incontinence articles and in separating water and aqueous components from hydrophobic liquids. An example of production method is as follows. Three grams of PES fibres and 6 g of polymer powder are poured into 250×10^{-6} m^3 beaker, 6.8 g of diluted dispersion solution is added and vigorously mixed. Because the polymer granulates adhered to each other and to the fibres, small to

Table 23.6 Characteristics of polyurethane superabsorbent fibres

Fibre	Linear density (denier)	Water absorbency (%)	Water solubility (%)
1	173	21.53	0.42
2	131	20.94	0.44

© Woodhead Publishing Limited, 2011

medium sized fibre flocks are obtained. After the product is dried at a temperature of 50–60°C a soft flocklike product is obtained.

- *US Patent 5304420* – Vinyl alcohol unit-containing polymer fibres having high moisture absorption and high water absorption (Hirakawa *et al*., 1994).

The patent describes fibres, yarns, and fibre products that have durability, high moisture absorption and high water absorption that are not lost even by dyeing or cleaning. The fibres are soft and bulky and feel like natural fibres. Additionally, they can be produced without any problems during the fibrisation step and allow the incorporation of colour. According to this invention the fibres are composed substantially of (i) a vinyl alcohol unit-containing polymer, in which the alcoholic hydroxyl group is modified, and (ii) another fibre-forming polymer phase. The fibres and yarns of this invention may be as long as monofilaments, or short fibres as staple ones, spun yarns, and blended yarns. They may be woven into fabrics, or they can be components of nonwovens, and final clothing and towels can made of these fibres and yarns.

- *US Patent 6783852 B2* – High-absorbent polyvinylalcohol fibres and nonwoven fabric comprising them (2004).

The aim of this invention was to provide PVA fibres of high water absorbency, good strength and elongation properties, and from which fabrics could be prepared. As a result of this invention cross-linked PAV fibres were prepared from a water-soluble polyvinyl alcohol, which satisfies the following requirements:

- Water absorption in water at 30°C, ranging from 10 to 100 times the weight of fibres
- Fibre diameter in water at 30°C, as a result of absorbing water ranging from 2 to 10 times diameter of fibres not having absorbed water
- Melting point ranging from 160 to 220°C, and a heat of fusion ranging from 40 to 100 J/g.

23.5 Applications of superabsorbents in medicine

Hydrogels were used for the first time in the production of contact lenses in 1960, when Wichterle and Lim obtained a cross-linked hydrophilic superabsorbent from 2-hydroxyethyl methacrylate (HEMA). Then hydrogels were characterised by a water absorption equal to 80 g/g of dry polymer mass. In the following years superabsorbents, in which the absorption was much greater, were obtained (from 40 to 1600 g/g dry polymer mass). At present, hydrogels are applied in medicine, pharmacy and tissue engineering. In the course of time the polymers under discussion have been widely applied in the mass production of surgical tampons and personal hygiene items (Bereś and Kałędkowska, 1992; Tyliszczak and Pielichowski, 2007).

© Woodhead Publishing Limited, 2011

23.5.1 Contact lenses

Poly(2-hydroxyethyl methacrylate) has been applied in the production of contact lenses up to the present day. This polymer has hydrophilic properties, due to the presence of an -OH group, which is why it is possible for oxygen to reach eye balls through the gel aqueous phase without any obstacles. When dry, this material has the properties of hard organic glass; whereas after the hydration, it becomes soft and flexible. Further research continues with regard to the properties of the hydrogel and its application possibilities (Bereś and Kałędkowska, 1992; Tyliszczak and Pielichowski, 2007; El Fray, 2005).

23.5.2 Systems for the administration of drugs

Materials in the form of hydrogel matrices make possible the uninterrupted or controlled release of incorporated drugs into body fluids once a device is implanted, injected or otherwise introduced into the organism. There are two variations in the concept of action of such systems. According to the first concept, release of small drug molecules takes place as a result of hydrogel swelling. According to the second concept, the drug-containing polymer matrix undergoes erosion, and diffusion of the drug into the surroundings is a function of the rate of biological decomposition (Tyliszczak and Pielichowski, 2007).

An example of drug release from a hydrogel matrix is a polymer obtained by Ravichandran. The copolymer synthesised with the participation of *N*-vinyl pyrrolidone, acrylic acid and poly(ethylene glycol) (poly[*N*-NVP-AA]-PEG) was pH-sensitive, biocompatible and biodegradable. The influence of pH on the degree of hydrogel swelling was examined in buffers with pH similar to that of gastric juice (pH 1.2) and intestinal juice (pH 6.8). The system swelled slowly in the acid environment of gastric juice, which allowed a prolonged time for drug release in the stomach as well as obtaining a localised release system (Gupta *et al*., 2002).

23.5.3 Hydrogels in tissue engineering

Swelling gels composed of acryloamide copolymers with acrylates and physiological salt solutions are applied as the environment for microorganism development as well as human and animal cells. Hydrogels, due to their physical properties, which makes them similar to soft tissues, and also due to biocompatibility, thrombogenicity, good permeability to the oxygen and other water soluble methabolites, create more efficient environments and ensure faster cell growth than the other materials applied so far. Superabsorbents are applied as matrices in tissue regeneration (Zdebiak and El Fray; 2006). Suitably prepared poly(ethylene glycol), poly(vinyl alcohol) based hydrogels or these based on poly(ethylene oxide) and poly(propylene oxide) copolymers are ideal substrates for the proliferation of cartilage cells (Zdebiak and El Fray 2006; Tyliszczak and Pielichowski, 2007).

© Woodhead Publishing Limited, 2011

23.5.4 Hybrid organs

Presently, work is pending on obtaining hybrid internal organs that could substitute for damaged organs such as pancreas or liver. A hybrid pancreas prototype has been built of living animal cells and a membrane that surrounds them and protects from destruction by the recipient's immunological system. The hydrogel membrane of poly(vinyl alcohol) shows biocompatibility with its surrounding. It does not become encapsulated by tissues and is permeable to oxygen, glucose and insulin. Prototypes of artificial kidneys, vocal cords and tendons have been constructed, based on cellulose or acrylates derivatives (Zdebiak and El Fray, 2006; Tyliszczak and Pielichowski, 2007).

23.5.5 Reconstruction of blood vessels and human muscle cells

According to Sakai (Sakai *et al*., 2008) hydrogel fibres that possess a cell-adhesive surface and are degradable via enzymatic reactions were developed for fabricating tubular constructs with smooth muscle cells (SMC) and endothelial cell (EC) layers similar to native blood vessels, in the collagen gel. The fibres were prepared by soaking hydrogel fibres from a solution of sodium alginate and gelatin contained bovine endothelial cells (BECs) in medium contained oxidised alginate (AO). BECs soaked in eight per cent AO show no reduction in viability within three hours of soaking. SMCs of mouse adhered and prolirefated on the AO cross-linked hydrogels. The researchers covered the surface of mouse SMCs by the hydrogel fibres containing BECs and embedded them in collagen gels. Then they degradated fibres using the alginate lyase to obtain channels in the collagen gels. A histological analysis of released ECs using a specific fluorescent dye revealed the formation of tubular structures with layered BECs and mouse SMCs (MSMCs) (Sakai *et al*., 2008).

The introduction of protein into polyacrylonitrile artificial muscle systems improved their responses. The micro-morphology and swelling/shrinking kinetics of hydrolysed polyacrylonitrite blend-soy protein (H-PAN/SP) hydrogel fibres have been studied. It was found that hydrogel fibres with a content of soy protein showed excellent and stable pH responses. In addition, the cross-linking density and temperature have an impact on the pH response of the hydrogel fibres. Studies of dynamic elongation and contraction behaviour assist in the understanding and control of pH response of H-PAN/SP hydrogel fibres (Yu and Gu, 2008).

23.6 Applications of superabsorbents in hygiene products and medical textiles

23.6.1 Application of superabsorbent polymers (SAPs) for hygiene products

The largest use of superabsorbent polymers is in personal hygiene products. These consumer products include, in order of volume of superabsorbents used, disposable

© Woodhead Publishing Limited, 2011

infant diapers, children's training pants, adult incontinence articles, and feminine sanitary napkins. AMCOL International Cooperation estimated their total superabsorbent polymers sold in 1995. The percentage of hygiene products based on superabsorbents is: 85% baby diapers 10% adult incontinence products, 3% feminine hygiene, and 2% miscellaneous (Pytlik *et al.*, 2000).

Baby diapers

Due to the fact that baby diapers create the largest application group of products they will be described the most precisely. The use of superabsorbent polymers revolutionised the diaper industry. Diaper manufacturers began to design diapers to take advantage of the amazing liquid retention ability of the polymer. Superabsorbent polymers absorb and retain, under a slight mechanical pressure, about 30 times their weight in urine. The swollen gel holds the liquid in a solid, rubbery state and prevents the liquid from leaking onto the baby's skin and clothing.

Many aspects must be considered in the design of the polymer matrix in the diaper core. The absorption rate of the diaper must not be slower than the urination rate of the baby, otherwise leakage will occur. The absorption rate of the composite is influenced by the absorption rate of the superabsorbent polymer. On the other hand, fast swelling of the polymer may or may not be desirable. In some diaper designs, fast swelling may cause the diaper to leak if the porosity and permeability of the composite are reduced. The absorption rate of superabsorbent polymers is affected by the maximum absorption capacity of the polymer and its particle size and shape. The placement of fast or slow absorbing polymers in the composite structure has important implications for the effectiveness of the composite. In addition, particle size, placement, and relative amounts play a large role in the optimisation of absorption. When the superabsorbent swelling is delayed in the wetting region of some diaper designs, there is more time to distribute urine through the diaper. By distributing liquid better throughout the diaper, there is less saturation of the core in the wetting region, so further wetness may be absorbed.

With refined understanding of the impact of superabsorbent polymer on the absorbent core in the early 1990s ultra-thin diapers became possible. The amount of cellulose pulp fluff used in these diapers was reduced by half, yielding a thinner diaper with a higher concentration of superabsorbent polymer in the absorbent core (Buchholz and Graham, 1998).

A separate layer of nonwoven fibres was added to improve urine distribution in the diaper. This distribution layer was placed between the composite absorbent core, which consists of the cellulose fibre and superabsorbent, and the porous cover sheet. The distribution layer had the lower absorbency than either the standard cellulose fluff or superabsorbent polymer and the lower density, which allowed for a fast liquid distribution within the diaper. The layer was made from either chemically cross-linked cellulose fibres or a non-absorbent nonwoven

© Woodhead Publishing Limited, 2011

material, such as polypropylene fibre, and it was sufficiently porous to allow liquid to pass through freely (Buchholz and Peppas, 1994).

Superabsorbent polymer in the granulate or powder form is added to baby diapers in basically two ways, layered or blended. In the *layered method*, powdered superabsorbent polymer first is scattered onto a layer of fluff pulp. The fluff is then folded, so that the polymer is located in a centralised layer in the absorbent structure. This structure is covered with a nonwoven fabric layer. In the *blended application*, the superabsorbent polymer first is mixed homogeneously with the fluff pulp. Then the mixture is laid down to give the absorbent structure, which is subsequently covered with a nonwoven fabric.

Absorbency under the load and stability of the gel against the shear are important properties of superabsorbent polymers and relate strongly to the diaper performance. Diaper leakage was closely correlated with the stability of gel to shearing. More rigid superabsorbent particles, created by increasing the cross-linking, allows for a higher gel modulus and helps the particle withstand the shearing from the baby's weight. Superabsorbent polymer producers have been interested in developing biodegradable diaper or other absorbent product. Articles incorporating biodegradable superabsorbents might be disposed of in municipal composting facilities or flushed down the toilet for degradation in domestic septic tanks or at municipal wastewater treatment plants. Several diapers claiming biodegradability have been marketed, but none has enjoyed a commercial success.

There are several reasons for the continued development of advanced superabsorbent polymers. Diaper manufacturers would like to reduce their manufacturing costs. A superabsorbent that can take the other role in the absorbent core, can displace other components in the core, in turn reducing raw material costs and simplifying construction. For example, a superabsorbent fibre that can provide rapid fluid absorption and adequate wicking and transportation of fluid could displace cellulose fluff in the absorbent core, leading potentially to a simpler or less expensive diaper. On the other hand, manufacturers of premium diapers seek to differentiate their products in order to demand a higher price. An advanced superabsorbent that presents marketable performance advantages, for example the biodegradability to the absorbent product, may be of special value to diaper manufacturers (Pytlik *et al*., 2000).

Adult incontinence products

Sheet-like absorbants for water and aqueous solutions, which can be applied in many technical and industrial end-uses including hygienic articles, such as baby diapers and adult incontinence products and wound dressings, have been developed by Stockhausen of Krefeld in Germany. They offer the possibility of fixing superabsorbent polymers (SAPs) in the form of powder or granulate into any desired arrangement in one or more sheets.

© Woodhead Publishing Limited, 2011

In US Patent 6051317 (Brueggemann *et al*., 2000) a superabsorbent sheet is disclosed to fully use the swelling capacity of the SAPs. The structure has an increasing absorptive capacity for water and aqueous liquids, particularly under the load. That structure contains: (i) at least one water-swellable synthetic and/or natural polymer; and (ii) at least one water-soluble synthetic and/or natural polymer.

The first polymer component, A, is fixed in a defined fashion within the matrix component, B, which has a sheet-like design. The matrix can be made from a wide range of water-soluble, film-forming synthetic polymers including polyvinyl alcohols, polyalkyl allyl ethers, polyglycol ethers, polyvinylpyrrolidones, polyacrylates and polymethacrylates, or natural polymers such as guar, alginates, agar-agar, xanthan, pectin and starch.

Preferred SAP materials include partially neutralised, slightly cross-linked polymers and copolymers of acrylic acid and acrylamide, graft polymerisates of starch as well as cross-linked starches and cellulose derivatives. Examples of suitable products include Favor and Stockosorb from Chemische Fabrik Stockhausen in Germany.

The inventors note that the grain size of the powdered SAP depends on the intended use of the structure. They add that the absorbent sheet for the use in feminine hygiene articles must be as thin as possible. The structure is manufactured by applying a viscous solution of matrix B on a surface, such as metal sheet, siliconised paper or a PTFE film, using spraying, spreading or knife-coating procedures. The water-soluble polymer is then sprinkled with the SAP component A, and the sheet thus obtained is dried at suitable temperatures and removed from the auxiliary surface used. The flexibility of the superabsorbent sheet can be varied by using additives such as plasticisers or plasticising agents, and also by using fillers. The absorption rate depends on the ratio of matrix material to SAP (Anon, 2000).

23.6.2 Hydrogel dressings

Moist hydrogel dressings, included into the third most modern dressing generation of materials are obtained from the mixture of natural polymers (agar-agar, gelatine, pectin) and synthetic polymers (poly(vinyl pyrrolidone) and poly(ethylene glycol)), which were placed in commercial packagings and subjected to sterilisation by the electron stream or gamma radiation. Hydrogel dressings are the most often used for burn wounds, but also for traumatic wounds, ulcerations and bedsores. Due to their considerable flexibility, they can be applied in any place of the body. Taking off the hydrogel dressing is very simple and painless. Skin regeneration and reconstruction in the course of cure with this kind of dressing takes place faster than with an application of traditional dressings (Szewczyk and Cwajda, 2005).

The main purpose of an ideal wound dressing is to keep the environment moist, at the same time removing the excess of effusion and any toxic particles. Sustaining

© Woodhead Publishing Limited, 2011

appropriate humidity thanks to the modern wound dressings prevents the appearance of a scab typical for dry wounds, which makes the wounds heal faster. A moist environment for a wound is of great importance in soothing pain through protection and prevention of irritation at nerve system endings (Alvarez *et al*., 1989).

Hydrogel wound dressings made of a three-dimensional hydrophilic polymer net, swell upon contact with water, retaining a great amount of it. The jelly mass of hydrogel is able to absorb effusion, maintain high wound moisture and allow the growth of cells and their migration. It also has good purifying properties through providing water to necrotic tissues.

In order to obtain a moist environment for the treatment of wounds, dextranomer wound dressings made from polysaccharides also might be used that in addition to effusion, form a gel that has significant properties for absorbing large particles (e.g. removal of bacteria from a wound when placed between the layers of grains of a wound dressing). Also available are polyester wound dressings in the form of plates or oval sponges, which are permeable to air. The contraindication for their use is wounds with a dry scab or black necrosis.

Alginate wound dressings made from natural polysaccharides obtained from sea algae absorb effuse and accelerate the coagulation processes (Tonnesen and Karlsen, 2002). Any excessive gel remnants remaining in the wound undergo biodegradation to glucose remnants and they do not cause any allergy symptoms. Wound dressings with superabsorbents should be activated with Ringer liquid. The activity of a superabsorbent is based on the softening and absorbing a necrotic tissue, rinsing and absorbing the pathogenic bacteria. The wound dressings described above can be changed every few days; the producers allow for some of them to be left even up to seven days. The absolute indication for a change of wound dressing is pain reported by the patient, the occurrence of fever, the inability of a wound dressing to absorb and, of course, slackening of fitting.

23.6.3 Covers for operating room tables

Superabsorbents can be applied to materials used in the clinical environment. Microtek Medical of Alpharetta, Georgia, USA, has introduced Mojave, a new material that has a superabsorbent core made via a patented process that involves the uniform distribution of superabsorbent polymers within a matrix of high-performance fibres. The barrier created by Mojave is impervious to blood and body fluids, viruses and bacteria, thereby providing improved protection to patients, healthcare workers and their equipment.

Furthermore, tri-laminate fabrics made with Mojave help to prevent cross-contamination from fluid run-off by aggressively trapping fluids and locking them into the superabsorbent core. The material also helps to minimise exposure to moisture and protects the integrity of the patient's skin by wicking fluids away and

© Woodhead Publishing Limited, 2011

locking them in the core. Mojave was initially manufactured as covers for the operating room tables (Microtek, 2010).

23.7 Applications of superabsorbents for comfort improvement

23.7.1 Description of work conditions

Wearing tight clothing to protect against chemicals increases energy expenditure. A similar situation exists when barrier clothing is worn by medical staff, especially surgery personnel. It was shown that applying clothing from coated fabrics increased energy expenditure by about 58.3 J/s in comparison with cotton ones (Holmer, 1995). It is especially difficult for the human organism to work in tight clothing at high temperatures. It was stated that even at low work intensities a worker in tight clothing made of coated materials and in a hot environment requires a shorter working period and longer rest breaks than in a moderate climate. Such conditions exist in many work stations, very often in the surgery room, where there is no air-conditioning system. The microclimate under tight clothing was characterised by a high increase of temperature and humidity, which after 20 minutes of work was saturated. Tight protective clothing loads the user organism and, first of all, influences the circulatory system negatively during physical effort (Holmer, 1995). An extreme example of such clothing is that used for protection against chemicals in the liquid and gas forms. It is produced from materials coated by synthetic polymers from both sides.

23.7.2 Types of new textiles with superabsorbent fibres

The authors decided to use superabsorbents as pads under the tight clothing to decrease the microclimate humidity under it. They were designed in the form of vests or single element, nonwoven inserts for clothing, gloves and shoes. Assuming that the mean perspiration during work in tight protective clothing is about 13.9×10^{-2} g/s, and time of work in such clothing is three hours, it is necessary to ensure about 2500 g/m^2 of the sorption volume on the 0.6 m^2 of the human body.

Ten absorptive nonwovens with different variants of Oasis fibre percentage (50, 30 and 15%) were produced. After absorption of water, superabsorptive fibres create a gel, which decreases the nonwoven's stability. They were used in two-component blends. The main raw materials of the blends were, successively: long-staple cotton (37×10^{-3} m), polypropylene (1.3×10^{-4} g/m, 38×10^{-3} m) and polyester (4×10^{-4} g/m, 62×10^{-3} m). Cotton was used because of its high hygroscopicity. It can help the superabsorbent to be highly efficient. Polypropylene and polyester have thermo-plastic characteristics, which can be helpful in finishing processes like pressing, laminating and strengthening. One planned nonwoven variant consisted of three components. The planned nonwoven components and nonwoven

© Woodhead Publishing Limited, 2011

Table 23.7 Variants of nonwovens

Nonwoven variant	Raw material content	Mass per square metre (g/m^2)	Thickness (mm)
A	50% Oasis 102/50% CO	150.6	3.32
B	30% Oasis102/70% CO	131.8	3.37
C	30% Oasis 102/70% CO needle punched with a cotton net of canvas weave	164.0	3.12
D	50% Oasis 102/50% polyester	204.7	2.32
E	30% Oasis 102/70% polyester	276.7	3.71
F	15% Oasis 102/85% polyester	197.3	3.02
G	50% Oasis 102/50% polypropylene	226.3	3.57
H	30% Oasis 102/70% polypropylene	203.9	3.01
I	34% Oasis102/33% CO/33% polypropylene sewn with the needle punched with cotton	240.9	2.99
J	50% Oasis/50% Amicor	190.5	3.86

characteristics are given in Table 23.7. The technological process of nonwoven production was carried out in the following climatic conditions: RH 40% and temperature 20 ± 3°C. Oasis fibres produced by Technical Absorbents were very slippery, without any crimp and had a very high absorption of humidity from the air, so the technological process was very difficult. Nonwovens (C and I) were strengthened by punching them with a cotton net of loop size $(5 \times 10) \times 10^{-3}$ m.

23.7.3 Assessment of textiles with superabsorbent fibres in the aspect of shaping the microclimate under the tight clothing

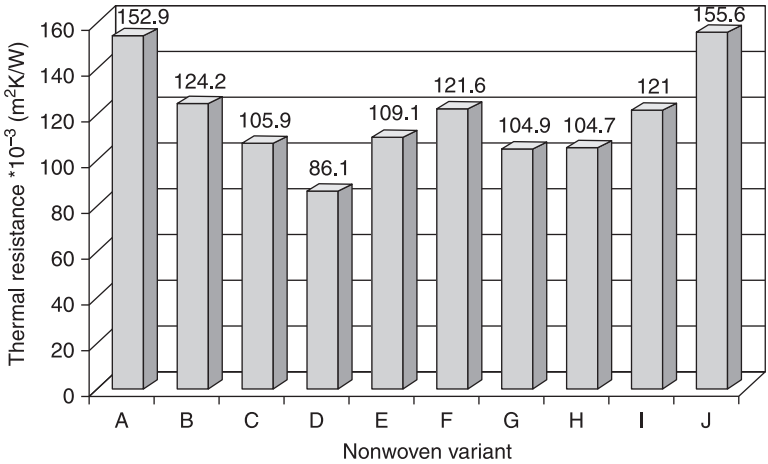
Results of measurements on materials

The nonwovens with a proportion of Oasis fibres underwent metrological assessment.

Thermal resistance

The clothing microclimate temperature is influenced by the heat flux depending on the fabric thermal resistance, the results of which are shown in Fig. 23.5. On the basis of analysis of the thermal resistance of basic nonwovens it can be stated that a majority of them is characterised by the high thermal resistance in the range 86.1×10^{-3} m^{2}K/W for the nonwoven D of thickness 2.32×10^{-3} m to 155.6×10^{-3}m^{2}K/W for the nonwoven J of the highest thickness 3.86×10^{-3} m. For absorbing pads under the tight protective clothing the lowest thermal resistance would be the best; therefore, from this point of view, the nonwoven D was assumed as the best one.

© Woodhead Publishing Limited, 2011

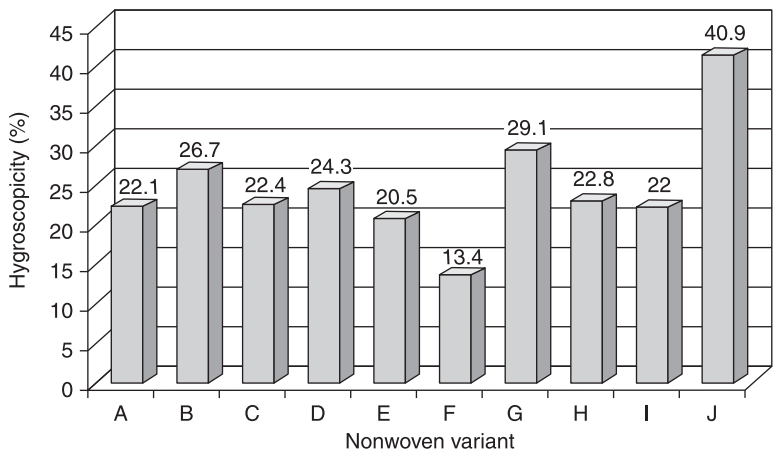


23.5 Thermal resistance of basic nonwovens.

Hygroscopicity

The absorption of water vapour from textile structures was analysed on the basis of their hygroscopicity. During the measurement according to the Polish standard (PN-P-04635, 1980), the samples were hung above a beaker filled with water and left for 4 hours in defined air conditions: the relative humidity was about 100% and the air temperature was 20°C. The results are presented in Fig. 23.6.

Considering the nonwovens, the results show that the materials with the higher content of superabsorbent fibres are characterised by the higher value of hygroscopicity, but it depends also on the content of the other fibres. The highest hygroscopicity (40.9%) was shown by sample J (50% Oasis/50% Amicor) and



23.6 Hygroscopicity of nonwovens.

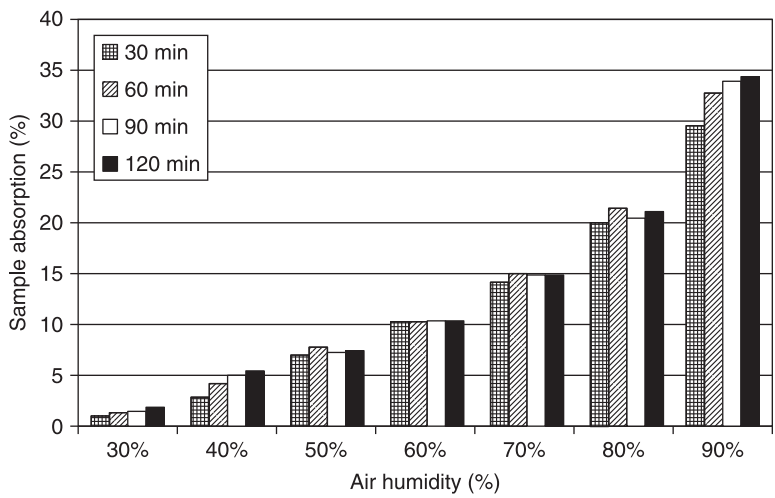
© Woodhead Publishing Limited, 2011

the lowest hygroscopicity (13.4%) was shown by the sample variant F (15% Oasis, 85% PES).

The studies of the hygroscopicity on the basis of the mentioned standard, do not fully imitate the real conditions of water vapour sorption that are present under protective clothing. In reality, the temperature in the microclimate under the tight protective clothing is at the level 30–35°C; while the relative humidity of the microclimate increases from 30% to 100% in a very short time period.

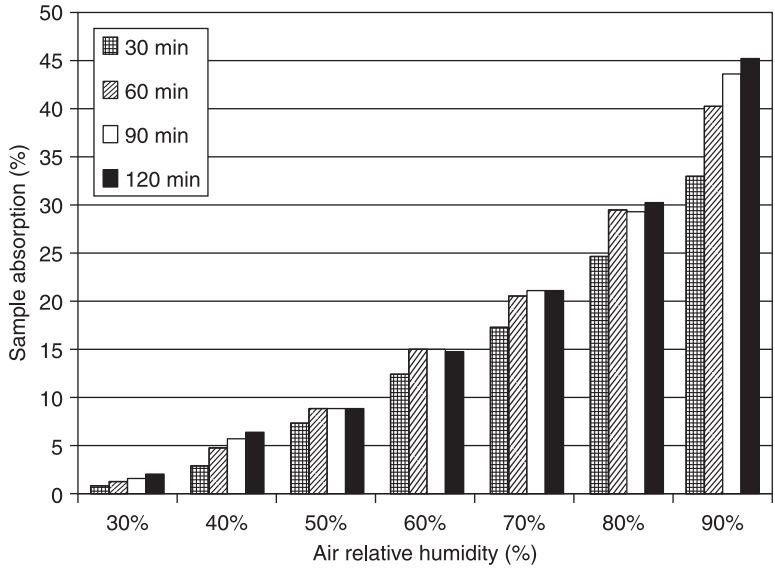
An analysis of Oasis fibre ability to absorb water vapour in time at the different air RH values was carried out. Samples of the nonwovens with superabsorbents were weighed and then dried at a temperature of 105°C to achieve a stable mass. After drying, samples were put into the microclimatic chamber at 30°C with the following values of the air relative humidity: 30%, 40%, 50%, 60%, 70%, 80% and 90%. At each of these relative humidities, an increase of mass was measured. Such measurements were done after 30, 60, 90, 120 and 180 minutes in relation to the dried sample. Values of the relative absorption of the water vapour in different relative humidities were calculated.

In Fig. 23.7 the results of the absorption of water vapour with regard to time (30, 60, 90 and 120 minutes) are presented for the nonwoven A (50% Oasis/50% CO); whereas in Fig. 23.8, the results are for the nonwoven G (50% Oasis/50% PP). Time of absorption does not significantly influence the amount of water vapour absorbed by these nonwovens in the range of RH 50–80%, but it has an influence when the RH is higher than 90%.



23.7 Absorption of water vapour over time by needle punched nonwoven A.

© Woodhead Publishing Limited, 2011



23.8 Absorption of water vapour over time by needle punched nonwoven G.

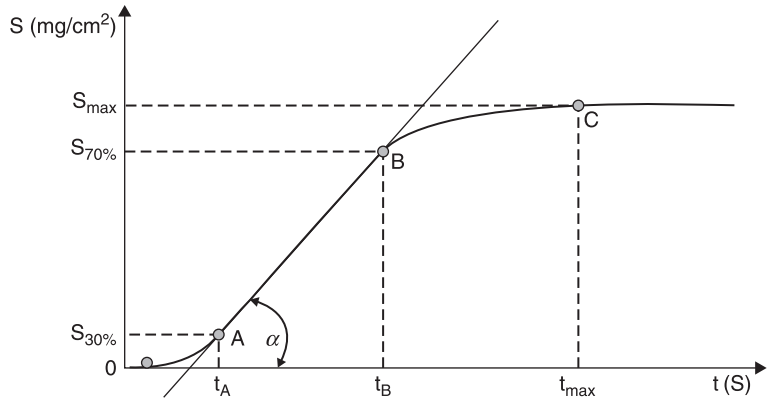
Dynamics of sweat sorption

The subjective feelings concerning the thermal comfort are influenced by the sorption of liquid for fabrics with a share of Oasis fibres. The sorption of liquid sweat by materials containing superabsorbents was determined using the method of material surface contact with the liquid (Królikowska and Goetzendorf-Grabowska, 2002). The method reflects the actual conditions of the garment use contacting the sweating human skin and allows the assessment of sorption phenomenon over time. The curve obtained, which is the basis for the analysis of parameters, defines the course of the sorption process (Fig. 23.9).

Proper sorption time is characterised by a rapid (rectilinear) increase of liquid mass in the sample volume. The tangent of the inclination angle of the AB segment to the *X*-axis defines the sorption velocity, $V_{30–70}$ (in µl/cm^2 s) (note: 1 µl/cm^2 s = 10^{-5} m/s). The saturation stage begins at the moment of abrupt decrease of the sorption velocity and lasts until the complete cessation of liquid mass increases. At that point the maximum sorption, S_{max}, expressed in microlitres (1 µl = 10^{-9} m^3) of the absorbed liquid per cm^2 (note: 1 cm^2 = 10^{-4} m^2) of the sample, is determined. The time corresponding to this point is defined as the total sorption time, t_{max} (s).

Assuming that during the use of tight protective clothing a continuous, intensive sweat secretion takes place and that it is used under the pressure of barrier clothing, the following measurement conditions have been adopted: pulsative liquid supply – 0.2423 µl, pressure exerted on the sample – 500 Pa.

© Woodhead Publishing Limited, 2011



23.9 Typical sorption curve.

In order to approximate the actual conditions associated with the sweat secretion, the tests were carried out using the acid sweat substitute based on the literature data concerning the chemical composition of sweat (PN-91/P-04913, 1991). For a comparative analysis of particular material variants, differing in mass per square metre values, a sorption effectiveness index (E) was calculated by relating the maximum sorption value (S_{max}) to the unit surface mass of the material m_p (Bartkowiak, 2006):

$$E = S_{max}/m_p \text{ (µl of sweat/mg of fabric)} \quad [23.1]$$

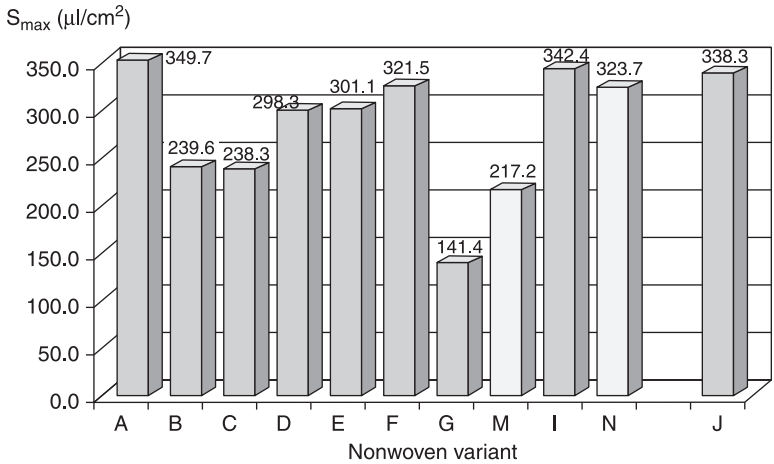
Preliminary tests showed that the sorption value is not directly proportional to the content of highly absorbent Oasis fibres in the material. That is why an additional parameter referred to as the Oasis sorption effectiveness index (E_{oasis}), characterising the quantity of liquid absorbed by the sample in relation to the unit mass of Oasis fibres, m_o, in the given material, was introduced (Bartkowiak, 2006):

$$E_{oasis} = S_{max}/m_o \text{ (µl of sweat/mg of Oasis in the fabric)} \quad [23.2]$$

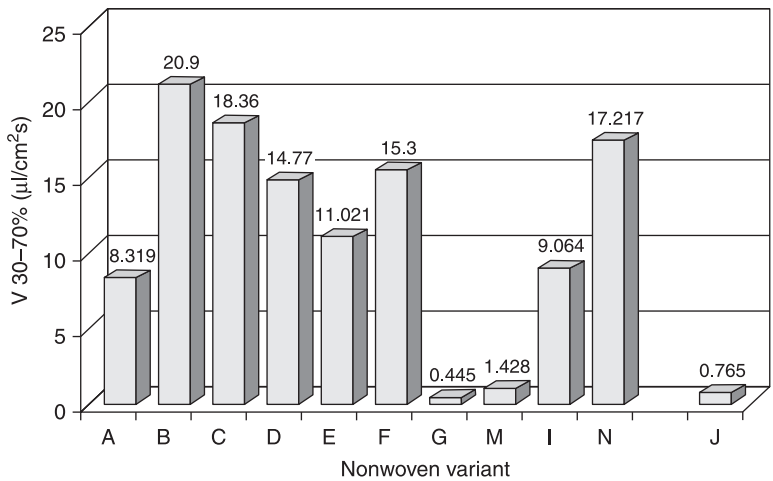
Results of sweat sorption parameters were analysed with respect to the influence on it of the raw material composition and share of Oasis fibres. In Fig. 23.10 the results of the maximum sorption for basic nonwovens are presented; whereas in Fig. 23.11 are the results of sorption velocity. In Fig. 23.10 and Fig. 23.11 the results of sweat sorption for the nonwovens M and N obtained by the hot pressing of needle punched nonwovens G and I, are also presented.

The maximum sorption is very important from the point of view of sorption efficiency of given material. The highest sorption, 340 µl/cm^2 (1 µl/cm^2 = 10^{-5} m^3/m^2), shows the nonwovens A and I which are a blend of Oasis fibres and cotton as well as the nonwoven J, which was produced with the proportion of antibacterial fibres Amicor. Very high sorption values (298.3–321.5 µl/cm^2) were obtained for nonwovens D, E, F made of Oasis/PES fibres. All nonwovens with an exception

© Woodhead Publishing Limited, 2011



23.10 Sweat sorption for nonwovens.



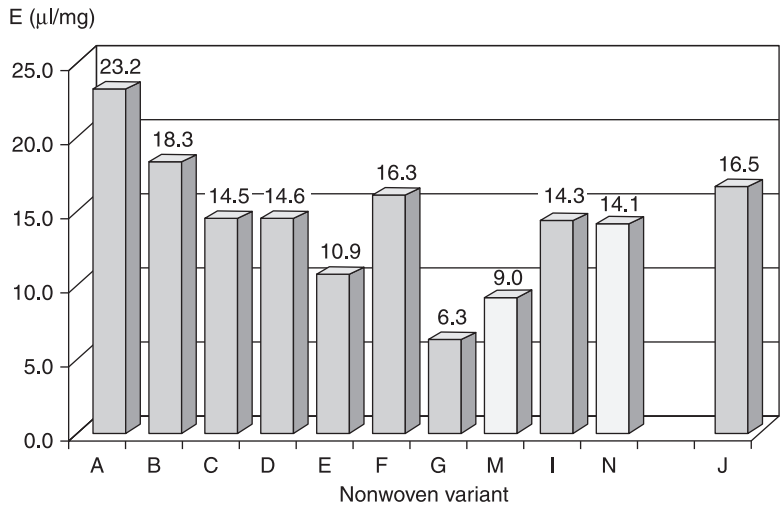
23.11 Rate of sweat sorption for nonwovens.

of G, M, J are characterised by the high liquid sorption. The nonwoven G made of Oasis and PP fibres blend has low maximum sorption (141.4 µl/cm^2) and the rate of sorption (0.44 µl/cm^2 × s) in comparison with the above mentioned nonwovens. It is worth pointing out that the nonwoven H, containing 30% Oasis/70% PP, does not demonstrate liquid sorption, so it is not shown in the figures. As a result of hot pressing the flattening of nonwoven G occurred, the large amount of Oasis fibres have contact with a wet surface of the device plate. Due to this reason, the increase of maximum sorption (variant M, sorption 217.0 µl/cm^2) and speed of sorption (2.12 µl/cm^{2}s) as well as diminishing the total time of sorption (from 342.5 s to 194.0 s) for the nonwoven G after the hot pressing was observed. The sorption

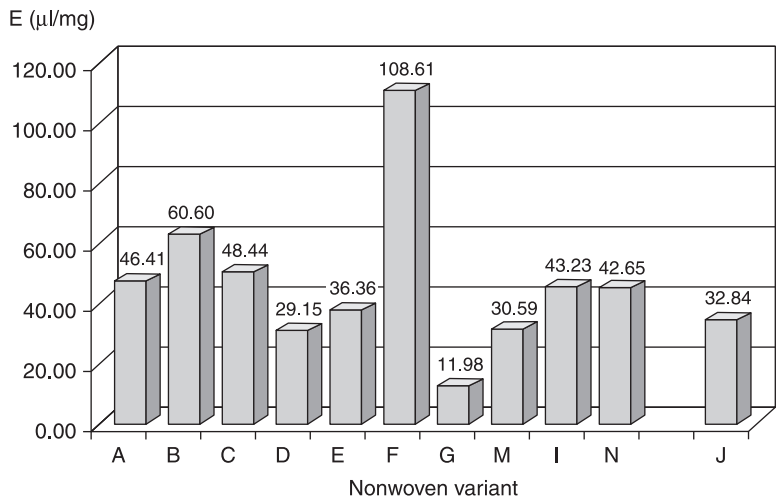
© Woodhead Publishing Limited, 2011

effectiveness for nonwovens is shown in Fig. 23.12; whereas the effectiveness in relation to the Oasis fibre share, is in Fig. 23.13.

By analysing the influence of cotton fibres on the sorption effectiveness it can be stated that using a blend of Oasis and cotton fibres is advantageous. Variants A and B are characterised by the highest sorption effectiveness and Oasis utility effectiveness (E_{oasis}). Sample F contains Oasis/PES blend and the results of its sorption of liquid are explained below. Decreasing the Oasis fibre content in the blend with cotton from 50% to 30% (sample B) decreases the sorption effectiveness



23.12 Effectiveness of sweat sorption for nonwovens.



23.13 Effectiveness of sweat sorption for basic nonwovens (E_{oasis}) in relation to Oasis fibre share.

© Woodhead Publishing Limited, 2011

from 23.2 µl/mg to 18.3 µl/mg. Considering the sorption effectiveness in relation to that applied in the nonwoven Oasis fibres (E_{oasis}) the nonwoven B (30% Oasis/70% CO) is characterised by the higher sorption effectiveness than the nonwoven A (50% Oasis/50% CO).

The cotton in the blend with Oasis fibres plays a very important role, because it transfers the sweat in the deeper layers of nonwoven. After adsorption of liquid the Oasis fibres have a gel form, and retain the liquid inside the fibres; they do not transfer it to successive fibres. Therefore, the textile structure with the Oasis fibres can absorb the liquid as a result of:

- Direct contact of Oasis fibres with liquid
- Transferring the liquid into the deeper layers by fibres absorbing the liquid and transferring it to Oasis fibres placed deeper (knot principle)
- Capillary transportation of liquid along the hydrophilic fibres.

The positive role of cotton fibres in nonwovens with a proportion of Oasis fibres relies on the ability of cotton to transfer the liquid into deep layers of the nonwoven and transmit it to the Oasis fibres, which do not have a direct contact with liquid.

Analysing the influence of raw materials applied in superabsorbent nonwovens on their sorption level it should be emphasised the satisfactory sorption and sorption dynamics of nonwoven blend Oasis/PES are different than that of nonwovens N made of fibres Oasis/PP. Nonwovens D, E, F have a very high maximum sorption (298.3–321.5 µl/cm^2). Nonwovens D and F are characterised by high sorption effectiveness (14.5 –16.3 µl/mg).

Comparing nonwovens D, F it can be stated that changing the amount of Oasis fibres from 50% to 15% caused an increase of sorption effectiveness (E) as well as an effectiveness in relation to the Oasis fibre share (E_{oasis}). Therefore, it can be concluded that in the case of nonwovens made of an Oasis/PES blend an increase in the proportion of Oasis fibre does not improve the sorption properties of nonwovens. Too large a packing factor of Oasis fibres, which do not transfer liquid, makes mutual liquid transportation between the material pores difficult.

Analysis of nonwovens with the same Oasis fibre content (50%) and of different transferring (synthetic) fibres, demonstrates the superiority of nonwoven D structure, in which PES fibres were used, over the nonwoven G, with a proportion of PP fibres.

The nonwoven D is characterised by a two-fold higher sorption effectiveness in relation to the applied Oasis fibres, E_{oasis} (Fig. 23.12 and Fig. 23.13). It is worth pointing out here the very high sorption effectiveness of nonwovens having the following Oasis fibre shares: 30 and 15% only in blends with PES fibres; whereas the nonwoven with 30% content of Oasis fibres and 70% of PP does not absorb sweat at all. The reason for the observed phenomena is the surface character of the fibres being used in the blend with the Oasis fibres. PES fibres, with a hydrophilic surface, alleviate capillary transportation in the material structure and, therefore, the liquid was transferred to the fibres which did not have direct contact with it.

© Woodhead Publishing Limited, 2011

The PP fibres, with a hydrophobic surface, which does not aid capillary transportation, do not have such an ability. In the Oasis/PP nonwovens only fibres that are in direct contact with a liquid can absorb it; the remainder do not transport liquid.

Such a conclusion is confirmed by liquid sorption results of the nonwoven I (34% Oasis/33% CO/33% PP). It is characterised by a very high sorption effectiveness E and E_{oasis} only due to the cotton fibre share in the structure. The nonwoven of similar Oasis fibre share, but in the blend with PP fibres (H) does not have any ability to absorb liquid, because the small amount of Oasis fibres were in contact with the sweat and could not transfer it further.

To sum up the results of sweat sorption dynamics it can be stated that the best parameters of sweat sorption dynamics can be obtained for the following nonwovens:

- Those containing the Oasis fibres and cotton (variants A, B and I)
- Those containing the Oasis fibres and PES (variants D, E and F).

Hot pressing of G nonwoven improved its sorption abilities very much. It can be stated that the nonwoven M is characterised by satisfactory sweat sorption.

23.8 Ergonomic tests

23.8.1 Studies of underwear and vests made from superabsorbent nonwovens

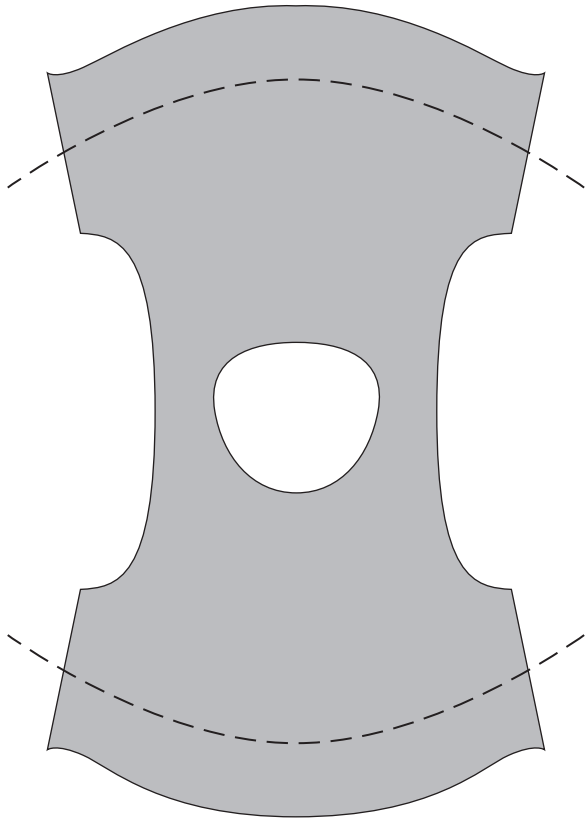
For further ergonomic studies with respect to clothing applications, a needle punched nonwoven cloth of the following composition (oa) was manufactured:

- 30% high sorption fibres Oasis 102
- 30% PES fibres (transmitting liquid)
- 30% PP fibres (binding)
- 10% bacteriostatic fibres 'Amicor +'.

In order to obtain a structure that could be used under tight protective clothing, the nonwoven cloth was subjected to the double sided calendaring (hot pressing). Waistcoats with the construction shown in Fig. 23.14 were cut out from the high sorption nonwoven Oasis (oa). On the sides the waistcoat can be tied with ribbons, which ensures contact of the nonwoven absorbing sweat with the underwear.

Taking into account that cotton underwear is universally used, studies were conducted with the traditional underwear made of cotton interlock knitted fabric stitch marked (ba) and waistcoat made of high sorption nonwoven (oa). The underwear used for the studies consisted of a T-shirt with long sleeves and long trousers. Cotton underwear was also used in a comparative variant, where the tight clothing without sweat absorbing waistcoats was studied. Characteristics of materials in the studied clothing variants are given in Table 23.8, and their

© Woodhead Publishing Limited, 2011



23.14 Construction of a waistcoat made of high sorption nonwoven.

Table 23.8 Study results of the nonwoven containing Oasis fibres and cotton knitted fabric

Symbol	Type of material	Mass per square metre (g/m^2)	Thickness (mm)	Hygroscopicity (%)	Heat resistance (m^2 K/W)	Water vapour resistance (m^2 Pa/W)
oa	Nonwoven with Oasis fibres	250	0.79	24.95	0.042	—
ba	Cotton knitted fabric	164	0.88	13.21	0.040	7.43

© Woodhead Publishing Limited, 2011

Table 23.9 Study results of water vapour sorption for nonwoven containing Oasis fibres and cotton knitted fabric

Symbol	Type of material	Sorption of water vapour (%)					
		at 70% humidity			at 90% humidity		
		after 30 min	after 60 min	after 90 min	after 30 min	after 60 min	after 90 min
oa	Nonwoven with Oasis fibres	12.0	12.8	13.1	20.8	24.6	25.6
ba	Cotton knitted fabric 100%	6.6	6.8	6.9	9.7	10.1	10.5

measurement results i.e. absorption of water vapour and sorption of sweat are given in Table 23.9 and Table 23.10.

The results presented indicate that the high sorption nonwoven containing Oasis fibres meets the requirements with respect to:

- Good thermal conduction
- High absorption of water vapour in the whole range of air relative humidity
- High sorption of sweat exceeding several times the mass of the sorption element.

The (oa) nonwoven, as a result of the hot pressing, is characterised by low thermal resistance at the level of resistance of cotton knitted fabric.

The results obtained (Table 23.8 and Table 23.9) indicate that the sorption of water vapour is over two-fold greater for the nonwoven containing the Oasis fibres in comparison with the cotton knitted fabric. After 30 minutes in the air humidity of 70% it reaches 12% (ba, 6.6%) and after 30 minutes in the air of 90% humidity, 20.8% (ba, 9.7%) (Fig. 23.15).

Nonwoven containing the Oasis fibres (oa) is characterised by more than four-fold higher sorption of acid sweat than the cotton knitted fabric (ba) compared with it. Both materials (oa) and (ba) show high and comparable sorption rate (Table 23.10).

23.8.2 Clothing sets for studies

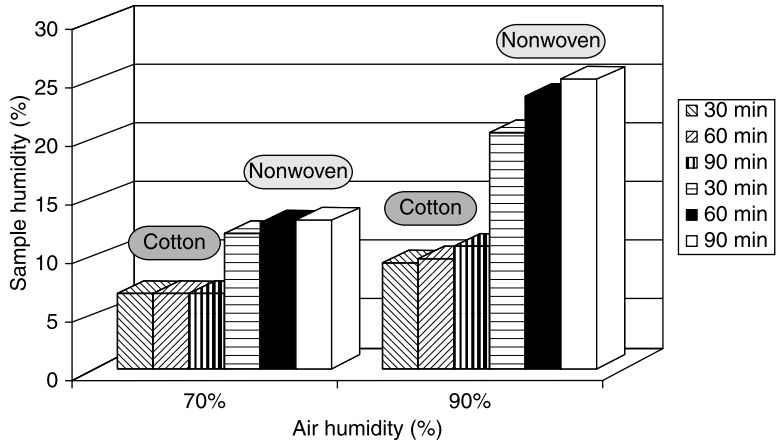
All studies were conducted on tight protective clothing (overalls) made of fabric coated with polyvinyl chloride, impermeable to water vapour, of mass per square metre 332 g/m^2 and thickness 0.285×10^{-3} m. Variants of the studied clothing sets with their designations are shown in Table 23.11.

© Woodhead Publishing Limited, 2011

© Woodhead Publishing Limited, 2011

Table 23.10 Study results of the dynamics of sweat sorption for the nonwoven containing Oasis fibres and of the cotton knitted fabric

Symbol	Type of material	Maximum sorption, S_{max} (μl/cm^2)		Sorption rate, $V_{30–70\%}$ (μl/cm^2/s)		t_{max} (s)	Sorption effectiveness, E (μl/mg)	Sorption effectiveness/ amount of Oasis fibres, E_{Oasis} (μl/mg)
		S_{max}	SD	V	SD			
oa	Nonwoven with Oasis fibres	492	11.7	26.1	2.95	56	19.68	65.6
ba	Knitted fabric, 100% CO	111	2.58	31.6	2.74	8	6.76	—



23.15 Sorption of water vapour for cotton knitted fabric (ba) and nonwoven absorbing sweat (oa).

Table 23.11 Variants of clothing sets for studies in the microclimatic chamber

No.	Marking	Clothing set
1	bb	Tight protective clothing + cotton underwear (comparative variant)
2	bk	Tight protective clothing + cotton underwear + waistcoat made of high sorption nonwoven

23.8.3 Test conditions and testing procedure of ergonomic tests

Five young healthy men, aged 21–22 years, took part in the studies. Their weights ranged between 62 and 91 kg and height between 1.75 and 1.88 m. Before taking part in the studies all the men underwent medical qualifying examinations. All took part in two types of tests, in which two clothing sets were tested. The participants undertook physical exercise of intensity 50 W on a Monark cycloergometer (Denmark).

Clothes were tested in a climatic chamber (Angelantoni Centro-Sud, Italy). The temperature inside the chamber was 21.3 ± 0.5°C, the air motion speed was 0.17 ± 0.04 m/s and the relative humidity of the air was 61 ± 6%. Duration of one test was 65 minutes. The tested person was doing physical exercise for 60 minutes and then for the next five minutes remained on the cycloergometer in an unchanged position in order to determine a restitution of heart rate. The following criteria of interrupting the tests were adopted:

© Woodhead Publishing Limited, 2011

- Internal temperature, 38.0°C
- Heart rate, 90% of the maximum value
- Subjective symptoms of tiredness or feeling bad
- Reaching 100% relative humidity at any measurement point on the skin.

After coming to the laboratory the tested person remained seated for 15 minutes. During this time the person had to drink 0.2 litre of mineral water to hydrate the body. Then the person's blood pressure and heart rate were measured. If the values were correct, the test was started.

During the test the following parameters were measured:

- Temperature and relative humidity on the skin: on the chest and in the middle of the back, recorded every 10 minutes.
- Internal temperature, recorded every 10 minutes.
- Heart rate (HR), continuous recording during the exercise and 5 minutes after finishing the exercise
- Body mass before and after the test.

During the test the following equipment was used: ECG (electrocardiography) electrodes (Biazet, Poland), sensors for measuring the temperature and relative humidity in the microclimate above the skin (Rotronic, Switzerland), thermocouple in the external acoustic duct for measuring internal temperature (Ellab A/S, Denmark). A Polar S-610 Precision Toolkit (Finland) was used for continuous recording of heart rate.

23.8.4 Discussion of test results

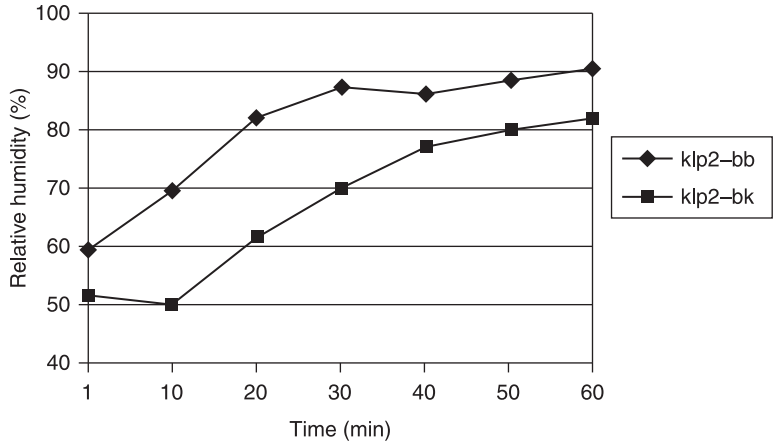
Results of studies on clothing in the microclimatic chamber are presented in Figs 23.16–23.19. It was found that, as expected, the humidity and temperature increased in all measurement points during work in the tight protective clothing.

Figure 23.16 and Fig. 23.17 show changes in the microclimate on the chest. It was found that the humidity for the variants of clothing with sweat absorbing elements (bk), was significantly lower than for the comparative variant (bb). During 20 min of the experiment the humidity for the variant of tight protective clothing without sweat absorbing elements exceeded 82%, whereas the variants with the sweat absorbing waistcoat reached only 61% for a variant with sweat absorbing elements (bk).

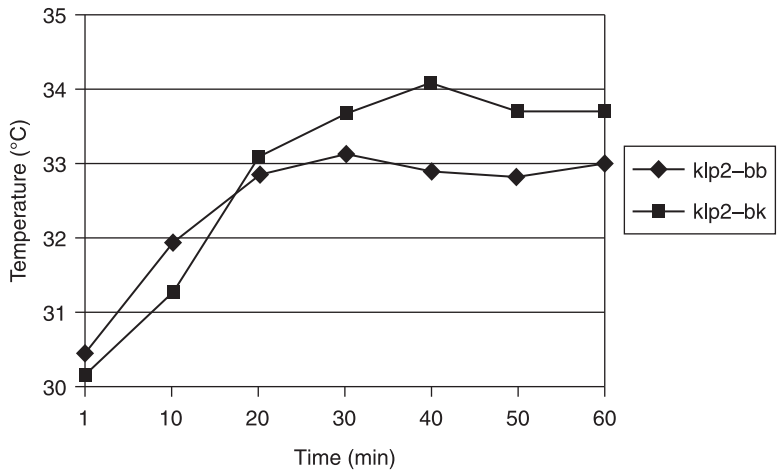
Humidity at the level of 80%, which was taken as the level causing discomfort for the user, was reached only after 50 min of exercise for the variants with the waistcoat. After 60 min of exercise the humidity reached: (bb) 90% and (bk) 81%.

Temperature in the microclimate on the chest on the left side was similar for all studied variants for the first 20 minutes of the experiment. After 20 minutes, the microclimate temperature started to increase slightly for the variants with the

© Woodhead Publishing Limited, 2011



23.16 Average changes of relative humidity under clothing – chest – during tests with different variants of clothing: bb, bk.

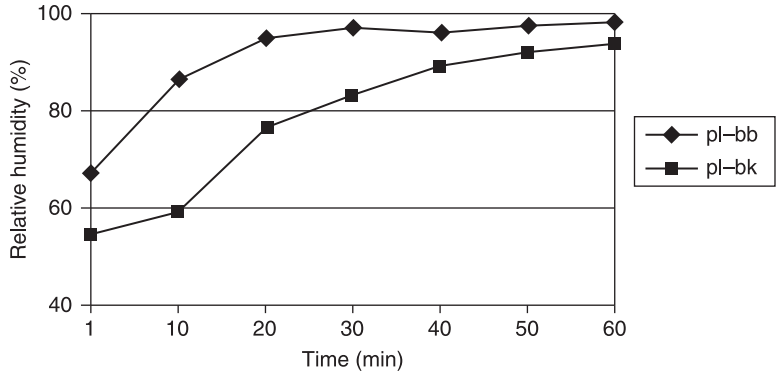


23.17 Average changes of temperature under clothing – chest – during tests with different variants of clothing: bb, bk.

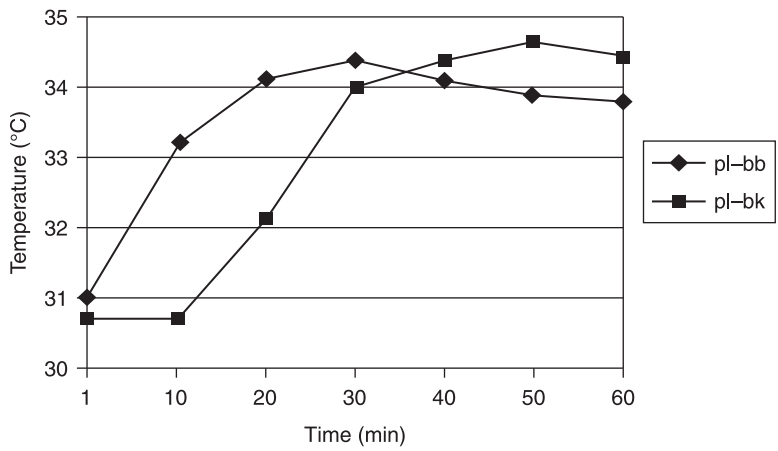
waistcoat made of nonwoven (bk, pk). In the 60th minute of the exercises, the microclimate temperature was, respectively: (bb) 33.0°C; and (bk) 33.7°C. The temperature was the lowest for the comparative variant (bb), because an additional clothing layer in variant bk was added.

Changes of humidity and temperature in the microclimate on the back are shown in Fig. 23.18 and Fig. 23.19. Intensive sweating on the back appears faster in the cotton clothing without sweat absorbing elements. In the test conditions only on the back a full saturation with water vapour was observed before the end of planned test period. Three of five tested men reached 100% of relative humidity

© Woodhead Publishing Limited, 2011



23.18 Average changes of relative humidity and temperature under clothing – back – during tests with different variants of clothing: bb, bk.



23.19 Average changes of temperature under clothing – back – during tests with different variants of clothing: bb, bk.

on the back only after 25 or 36 minutes of the test. In the other variant, with sweat absorbing elements, the test could last 60 minutes without full saturation of air under the clothing with water vapour.

Application of waistcoats made of high absorption nonwoven in the sets of tight protective clothing caused a significant decrease of microclimate humidity. After ten minutes of exercise, the humidity on the back for the variant without the sweat absorbing waistcoat reached 87% and for the variants with waistcoats only: (bk) 59%, in the 20th minute of the exercise: the variant without the waistcoat (bb) 95%, and variants with the waistcoat: (bk) 77%.

The temperature in the microclimate on the back was lower for variant bk up to the 35th minute of the experiment. From that moment the temperature on the back

© Woodhead Publishing Limited, 2011

for variants (bk) was slightly above the temperature of the microclimate for variant (bb) and at the end of the experiment differed by 0.7°C, this difference was not statistically significant.

In general, the humidity was higher in the variant of clothing with the cotton underwear without sweat absorbing elements in comparison with the variant with sweat absorbing waistcoats. On the basis of the statistical analysis conducted it was shown that in the 10th, 20th and 30th minutes of the test the differences in relative humidity under the clothing on the chest and the back were statistically significant ($p < 0.05$) between the variant of clothing with the cotton underwear without sweat absorbing elements and the variants of clothing with the sweat absorbing waistcoat. These results indicate a positive impact of sweat absorbing elements as they enable longer use of the types of clothing studied, with slower increase of relative humidity under the clothes.

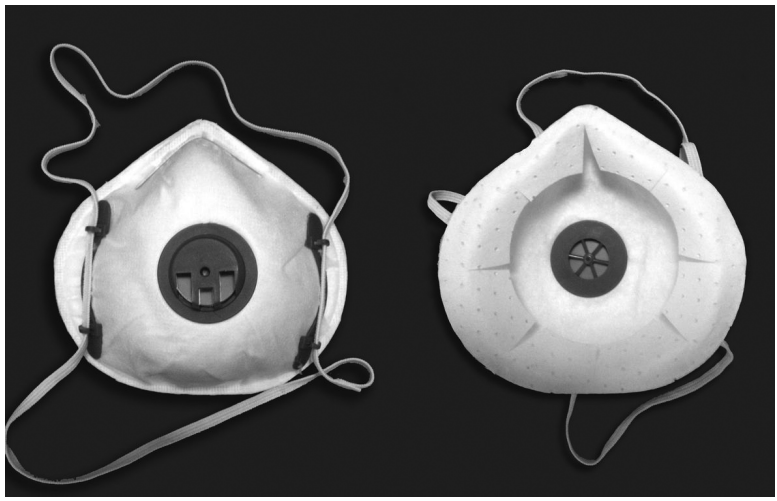
Summing up, the results of ergonomic tests of tight protective clothing, one can say that application of sweat absorbing elements in the form of a waistcoat under the tight protective clothing considerably reduced the humidity of the microclimate under the tight protective clothing. Due to the fact that elements made of high sorption nonwoven constitute an additional layer in the clothing set and may contribute to accumulation of heat, a small increase in the temperature of the underclothing microclimate was observed.

23.9 Application of superabsorbent materials in half masks

Using filtering half masks is very often connected with a discomfort that is the direct cause of not applying them according to their design or not using them at all. The most frequent reason of not using filtering half masks is irritation caused by them, even allergies among the users in places, where half masks touch the face (cheeks, chin or nose), which is the result of higher humidity of air in and around the inner part of the half mask. Humid air causes an accumulation of water particles and swelling of the filters that are used as a material of the half mask, as a result of which a coarse layer that causes skin irritation is created.

For construction of a filtering half mask FFP3 D type with a layer absorbing humidity, an innovative technology of joining superabsorbent fibres Oasis 102 with filtering ones was used in the Central Institute for Labour Protection, National Research Institute (CIOP-PIB). Applying this technology, construction of a filtering half mask was prepared with the nonwoven absorbing water vapour, which was placed inside the cap and adjusted to the needs of users of the filtering half masks (Fig. 23.20). The layer absorbing the humidity directly absorbs sweat and water vapour, thus efficiently limiting the discomfort caused by the rough surface of the filtering nonwoven fitted tightly to the skin and therefore prolonging the time of the half mask's usage.

© Woodhead Publishing Limited, 2011



23.20 Filtering half mask with a layer absorbing humidity made from nonwoven with Oasis 102 fibre.

The key solution of the layer absorbing humidity is optimising the amount of blended raw material of the nonwoven absorbing humidity, so that it keeps the optimal ability to absorb water vapour and not create an additional barrier for the basic function of the filtering half mask.

The prepared content of the raw material blended has no influence on the process of filtration; its efficiency remains at the highest, third level of protection (FFP3), at the same time causing no increase in the air flow resistance for the inhaled and exhaled air.

Furthermore, the accepted content does not cause any excessive collection of humidity inside the half mask's construction and because of that the half mask does not add any weight to the user's face, which could be tiresome during use. Through placing an additional, tight fit to the face layer, with a given shape inside the half mask's construction, a solution that guarantees an appropriate adjustment was obtained. Assuring an appropriate adjustment guarantees sustaining the effectiveness of the half mask's tightness, which from the point of view of functioning of equipment of such type, is the basic criterion of selection and correct usage.

The filtering half mask absorbing the humidity complies with the European standard of PN-EN 149+A1:2009 (2009) together with the suggested changes that amend the requirements connected with keeping the appropriate level of penetration towards aerosols in time.

23.10 Conclusions

Summing up, the chemical structure, form of appearance and a wide range of applications for superabsorbents in different areas of medicine and in personal

© Woodhead Publishing Limited, 2011

comfort has been shown. The advantages of the use of superabsorbents are numerous and obvious. Great progress in the development of superabsorbents is still being seen as well as new methods for their application. We expect that new and better (more efficient) solutions will continue to be invented, and that additional practical applications for superabsorbents remain to be discovered.

23.11 References

Ackers P J (1997). 'The future for superabsorbent fibres', *Tech Textile Int*, 2.

ADM (2010). Superabsorbents, Archer Daniels Midland Company. Available: http://www.adm.com/en-US/products/industrial/superabsorbents/Pages/default.aspx [Accessed 12 July 2010].

Alvarez O, Rozint J and Wiseman D (1989). 'Moist environment for healing: Matching the dressing to the wound', *Wounds*, 1, 35–51.

Anon (2000). Sheet-like superabsorbent structures, Medical Textiles. Available: http://findarticles.com/p/articles/mi_hb5987/is_2000_Nov/ai_n32008400/ [Accessed 12 July 2010].

Bartkowiak G (2006). 'Liquid sorption by nonwovens containing superabsorbent fibers', *Fibres Textiles East Eur*, 1, 57–61.

Bartkowiak G and Szucht E (2002). 'Liquid sorption in two layer packets of structuraly differentiate knitted materials', *Fibres Textiles East Eur*, 4, 45–48.

Bereś J and Kałędkowska M (1992). 'Super-absorbency', *Chemik*, 3, 59–61.

Brueggemann H, Dahmen K, Lehwald D and Theilmann R (2000). 'Sheet-like superabsorbent structures'. U. S. Pat. 6051317.

Buchholz F L and Graham A T (1998). *Modern Superabsorbent Polymer Technology*, John Wiley & Sons, New York.

Buchholz F L and Peppas N A (1994). *Superabsorbent Polymers: Science and Technology*, American Chemical Society, Washington.

Chen and Park K (2000). 'Synthesis and characterization of superporous hydrogel composites', *J Control Release*, 65, 73–82.

Degussa data sheet (2010). High performance polymers. Available: http://www.degussa-hpp.com/ [Accessed 18 July 2010].

El Fray M (2005). 'Multiblokowe elastomery termoplastyczne i żele polimerowe reagujące na bod ce zewnętrzne', *Elastomery*, 4, 10–14.

Flory P (1953). *Principles of Polymer Chemistry*, Cornell University Press, New York.

Glados S and Maciejewski M (1998). 'Hydrogels. Synthesis and applications', *Wiadomoœci Chemiczne (Chemical News)*, 52, 101–123.

Greger R and Windhorst U (1996). *Comprehensive Human Physiology: From Cellular Mechanisms to Integration*, Springer, Berlin.

Gupta P, Vermani K and Garg S (2002). 'Hydrogels: from controlled release to pH-responsive drug delivery', *Drug Discovery Today*, 7(10), 569–579.

Hirakawa K, Tanaka K, Kawamoto M and Tsuda T (1994). 'Vinyl alcohol unit-containing polymer fibers having high moisture absorption and high water absorption'. U. S. Pat. 5304420.

Holmer I (1995). 'Protective clothing and heat stress', *Ergonomics*, 38, 166–182.

Inada S, Kobayashi S, Taniguchi J, Mizuki S, Kamada H and Nishiyama M (2004). United States

© Woodhead Publishing Limited, 2011

Kiatkamjornwong S, Punchareon P (1999). 'Influence of reaction parameters on water absorption of neutralized poly(acrylic acid-*co*-acrylamide) synthesized by inverse suspension polymerization', *J Appl Polym Sci*, 72(10), 1349–1366.

Knack I and Beckert W (1991). 'Superabsorbent fibre flocks, methods for their production and application'. U. S. Pat. 5002814.

Knopf R J, Matthews V E and Jones A P (1976). 'Polyurethane hydrogel fibers and tapes and composites with natural and other synthetic fibers or films'. U. S. Pat. 3940542.

Królikowska H and Goetzendorf-Grabowska B (2002) 'Metoda oceny powierzchniowej chłonnoœci cieczy przez wyroby włókiennicze', *Przegląd Włókienniczy*, 11, 5–6.

Kuś H, Misterka S, Pielka S and Juszkiewicz M (1998). 'Miejscowe leczenie ran oparzeniowych i urazowych hydrożelowym opatrunkiem Geliperm.', *Polimery w Medycynie*, 4, 211–217.

Marszałek A, Bartkowiak G and Łêżak K (2009). 'Physiological effects of a modification of impermeable protective clothing construction', *Int J Occup Safety Ergon*, 1(4), 61–73.

Martini S (1998). Superabsorber und ihre Anwendungrn, *Melliand Textilberichte*, 10, 717.

Microtek Medical (2010). Product data sheet. Available: http://www.microtekmed.com/index.htm [Accessed 12 July 2010].

Mitchell R L, Muller T E, Stevens H D and Tabke R S (1972). 'Process for forming hydroxyethyl cellulose fibers having high water absorption and high water retention properties'. U. S. Pat. 3670069.

Nakanishi M. Sakuari A and Kobayashi T (1988). 'Absorbent article'. U. S. Pat. 4721647.

Nałęcz M (2002). *Biomateriały*, PAN, Warsaw.

Oasis Fibre Superabsorbent (2010). Product Data Sheet. Available: http://www.techabsorbents.com/EN/SAF [Accessed 12 July 2010].

Patent 6783852 B2, (2004). 'High-absorbent polyvinyl alcohol fibers and nonwoven fabric comprising them'.

PN-91/P-04913 (1991). 'Textiles. Determination of colour fastness to perspiration', Polish Standardization Committee, Warsaw.

PN-EN 149+A1:2009 (EN 149+A1:2009). 'Respiratory protective devices. Filtering half masks to protect against particles. Requirements, testing, marking', Polish Standardization Committee, Warsaw.

PN-P-04635 (1980). 'Methods of fabric assessment – determination of higroscopicity', Polish Standardization Committee, Warsaw.

Polaczek J, Dziki E and Pielichowski J (2003). 'Characteristics of hydrogel matrixes – biomedical applications', *Polimery*, 1, 2003, 61–65.

Pytlik E, Molino D and Moritz J (2000). Superabsorbent polymers, Available: http://www.eng.buffalo.edu/courses/ce435/Diapers/Diapers.html [Accessed 12 July 2010].

Rongan (2004). SAP Powder. Available: http://www.china-rongan.com/madetail.asp?prID=41&name=SAP%20Powder [Accessed 12 July 2010].

Roweton S, Huang S J and Swift G J (1997). 'Poly(aspartic acid): synthesis, biodegradation, and current applications', *Environ Polym Degrad*, 3, 175–181.

Sakai S, Yamaguchi S, Takei T and Kawakami K (2008). Oxidized alginate–cross-linked alginate/gelatin hydrogel fibers for fabricating tubular constructs with layered smooth muscle cells and endothelial cells in collagen gels, *Am Chem Soc*, Available: http://pubs.acs.org/doi/abs/10.1021/bm800286v [Accessed 12 July 2010].

Solari M (1994). 'Evaluation of the mechanical properties of a hydrogel fiber in the development of a polymeric actuator', *J Intell Mater Syst Struct*, 5(3), 295–304. Available: http://jim.sagepub.com/cgi/content/abstract/5/3/295 [Accessed 12 July 2010].

© Woodhead Publishing Limited, 2011

Szewczyk M T and Cwajda J (2005). 'Wound healing materials of new generation infections', *Your Health*, Available: http://www.zakazenia.org.pl/index.php?okno=7&id=123&art_type=14 [Accessed 12 July 2010].

Szlezyngier W (2000). Man-made materials, vol. 3, FOSHE, Rzeszów.

Tonnesen H H and Karlsen J (2002). 'Alginate in drug delivery system', *Drug Dev Ind Pharm*, 26(6), 621–630.

Tyliszczak B and Pielichowski K (2007). 'Characteristic of hydrogel matrices - biomedical application of polymeric superabsorbents', Technical Journal. *Chemistry*, R. 104, z. 1-Ch, pp. 159–167.

Yu L and Gu L (2008). Hydrolyzed polyacrylonitrile-*blend*-soy protein hydrogel fibers: a study of structure and dynamic pH response, *Soc Chem Ind*, Available: http://www3.interscience.wiley.com/journal/121520265/abstract?CRETRY=1&SRETRY=0 [Accessed 12 July 2010].

Zdebiak P and El Fray M (2006). 'The perspectives of polymeric hydrogels and thermoplastic elastomers as cartilage-like materials', *Inżynieria Biomateriałów*, (54–55), 27–35.

© Woodhead Publishing Limited, 2011

24

Nanofibrous textiles in medical applications

L. VAN DER SCHUEREN and K. DE CLERCK, Ghent University, Belgium

Abstract: Nanofibrous textiles may have a great potential in the medical field because of their unique characteristics that meet the criteria for medical applications. After a general introduction on nanofibres, this chapter will elaborate on the possibilities of nanofibres in wound dressings, drug delivery systems and tissue engineering applications. These case studies will prove the enormous potential of nanofibres in various medical domains.

Key words: nanofibres, electrospinning, wound dressings, drug release systems, tissue engineering.

24.1 Introduction

In this chapter the possibilities of nanofibrous textiles in medical applications are discussed. First, a general description of nanofibrous textiles is given. The definition of nanofibres, the possible production processes and the common characteristics of nanofibres are discussed. The emphasis herein lies on the process of electrospinning. In the following section the main applications of nanostructures in the medical field are shown, namely wound dressings, drug release systems and tissue engineering systems. For each application field, the required properties for that field, how nanofibrous structures can support these properties and which polymers are used to realise them, are discussed. Subsequently, the performance of nanofibrous structures is compared with the performance of the standard materials used for this application. At the end, some future trends are stated and this from different points of view, including the raw materials, the process itself and possible post-treatments.

24.2 Nanofibrous textiles

24.2.1 Nanofibres

Nanotechnology is a booming research field in all scientific domains. In the textile industry the focus herein lies on the development of extremely fine fibres. A distinction can be made between microfibres, submicron fibres and nanofibres, the last having diameters smaller than 500 nm. Nanofibres provide a connection between the nanoscale and macroscale world since, while the diameters are in the nanometre range, the lengths can reach kilometres.

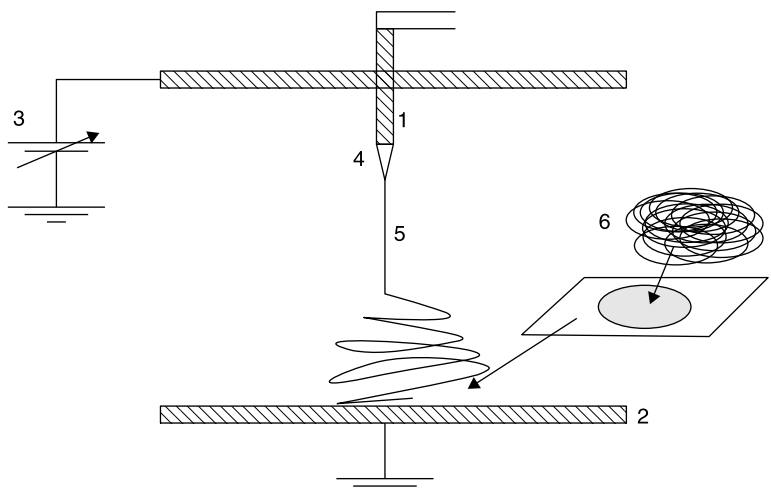
© Woodhead Publishing Limited, 2011

24.2.2 Production process

Several methods exist to produce nanofibres. Electrospinning is, however, the only well established technique that is increasingly being applied in industry (Greiner and Wendorff, 2007). Therefore electrospinning will be discussed in more detail in the first section while the other techniques will be combined in the second one.

Electrospinning

Electrospinning is a relatively simple process to produce nanofibres from polymer solutions. Electrospinning from direct polymer melts, instead of polymer solutions, is also possible but relatively few studies on this matter have been reported due to some underlying difficulties. Moreover, only submicron fibres can be obtained by melt electrospinning (Lyons *et al*., 2004; Larrondo and Manley, 2003; Zhou *et al*., 2006). Therefore, the general principle of electrospinning from polymer solutions will be explained (see Fig. 24.1). Electrospinning relies on electrostatic forces obtained by applying an electrical field between the tip of a nozzle (1), through which the polymer solution is flowing, and the collector plate (2) by a DC voltage source (3). This electrical field causes the distortion of the polymer solution from a spherical pendent drop to a conical shape, known as the Taylor cone (4). Once the electrostatic forces overcome the surface tension of the polymer solution at the nozzle, a jet stream (5) is drawn from the tip of the nozzle. On its way to the collector plate, the jet becomes unstable due to interaction



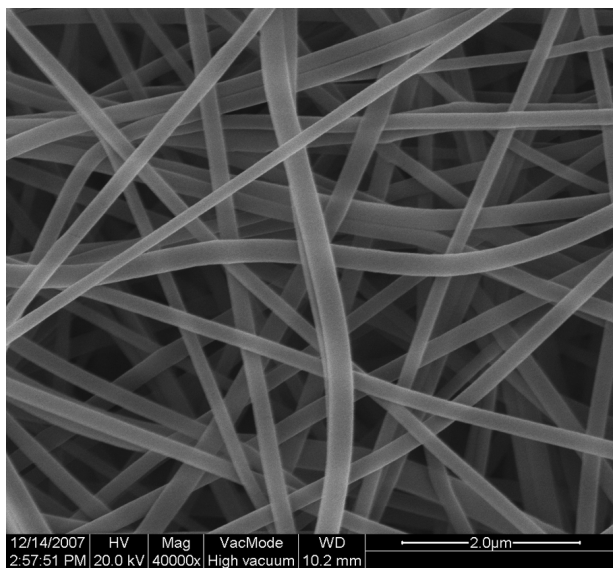
24.1 Electrospinning set-up: (1) nozzle, (2) collector plate, (3) DC voltage source, (4) Taylor cone, (5) jet, (6) non-woven.

© Woodhead Publishing Limited, 2011

of the charges with the external electrical field and solvent evaporation, which causes bending and splaying. These two processes cause the elongation of the jet and the so-produced nanofibres are deposited randomly on the collector plate as a nonwoven structure (6). A scanning electron microscope (SEM) image of a typical nonwoven structure is shown in Fig. 24.2.

The process of electrospinning may seem quite simple, there is a whole range of parameters influencing the production process. These parameters are divided into three groups: processing, solution and ambient parameters. The process parameters include the flow rate, the tip to collector distance and the voltage. The solution parameters contain the viscosity, the molecular weight, the molecular weight distribution, the solvent(s), the conductivity and the surface tension. Ambient parameters are the temperature, the humidity and the air velocity. This enormous range in parameters gives a variety in possible nanofibre structures with diverse properties.

Electrospinning is currently the most promising technique to produce continuous nanofibres on a large scale with diameters varying between nanometres and microns (Greiner and Wendorff, 2007). The technique provides the possibility to achieve controlled fibre diameters and to work with a variety of polymers and potential additives. Until now, more than 100 polymers, both synthetic and natural, have been successfully spun into ultrafine fibres using the electrospinning technique.



24.2 Scanning electron microscope (SEM) image of an electrospun nonwoven.

© Woodhead Publishing Limited, 2011

Other techniques

There are other approaches to produce ultrathin fibres. All of them show, however, some limitations that do not occur with electrospinning and therefore they will be only briefly discussed. The drawing process is similar to dry spinning and is able to produce very long, single nanofibres. The applied material must, however, resist strong deformations and should be cohesive enough to support the stresses developed during pulling. This requirement is not necessary in electrospinning where the elongation is carried out contactless (Ondarcuhu and Joachim, 1998; Li and Xia, 2004).

The template synthesis system uses a nanoporous membrane as a template to produce nanofibres of a solid or hollow shape. The desired material is synthesised within the pores of the membrane. This process is capable of producing nanostructures out of various raw materials and polymer nanofibrils with diameters of 3 nm can be obtained. In contrast with the drawing technique, template synthesis is not able to produce one-by-one continuous nanofibres. Moreover the method is inherently slow (Martin, 1996; Li *et al*., 2005b; Ikegame *et al*., 2003; Feng *et al*., 2006).

In a phase separation procedure different steps to form a highly porous three-dimensional interconnected nanoporous network are included namely polymer dissolution, phase separation and gelation, solvent extraction from the gel with water, freezing and freeze-drying under vacuum. The process is however again time-consuming and limited to specific polymers (Ma and Zhang, 1999; van de Witte *et al*., 1996).

Self-assembly is the autonomous organisation of components into patterns or structures as a consequence of specific, local interactions among the components themselves and is able to produce a nanofibrous network (Whitesides and Grzybowski, 2002). This process is however complex and time-consuming.

Meltblown and 'island in the sea' processes show a high productivity. In meltblowing, polymer melts are pushed under relatively high pressure through an orifice die. Fibres are then drawn by a jet of hot air. The fibres so obtained have diameters in the range of 500 nm to 2 μm. Fibre break-up instabilities represent a fundamental limit to the smallest fibres achievable by meltblowing (Ellison *et al*., 2007). In the 'island in the sea' technique a bicomponent fibre is spun. This fibre exists out of many island fibres arranged in a sea component that is removed afterwards by extraction. Nanometre size fibres can be obtained but strong requirements for the applied polymers make this technique relatively limited (Nakata *et al*., 2007).

24.2.3 Properties of nanofibrous structures

By reducing the diameters to nanometre scale values, specific and unique characteristics for fibre materials appear which turn nanofibre structures into

© Woodhead Publishing Limited, 2011

materials suitable for a whole range of applications. These properties include large specific surface area (up to 100 $m^2 g^{-1}$), high porosity (up to 95%) and small pore sizes (50 to 200 nm). Because of the large surface area, a nano nonwoven is capable of absorbing fluids very efficiently (Fang *et al*., 2008). Nanofibre mats possess a very flat surface because roughness is determined at nano-level (De Vrieze *et al*., 2007). Also the mechanical performance (e.g. stiffness and tensile strength) may be superior to any other form of the material (Huang *et al*., 2003). Another important characteristic of a nanofibrous structure is the flexibility to form a wide variety of sizes and shapes (Liang *et al*., 2007). Moreover the properties of a nanofibrous mat can be tuned, by modifying the parameters, to satisfy the needs for specific applications.

24.3 Applications of nanofibres in the medical field

Almost all human tissues such as bone, cartilage, skin etc can be considered as nanofibrous systems. Therefore a man-made nanofibrous structure is, in cases of a defect or problem in the natural system, the ideal candidate to mimic the native extracellular matrix (ECM) and assist the healing process. The nanoscale is particularly relevant for biomedical applications since viruses and bacteria have dimensions in this order. In the next sections the use of nanofibres in the medical world will be explored, starting with wound dressings and drug release systems, and ending with tissue engineering applications.

24.3.1 Wound dressings

Wound healing is a process of regenerating dermal and epidermal tissues. In severe wounds, no more cells are available to set up this regeneration except at the wound edges. This induces a long healing process and a high risk of the development of scar tissue (Marler *et al*., 1998). Another problem that arises when using a standard wound bandage on strong exuding wounds is the rapid saturation by body fluid of the bandages. This results in a short life-time of the wound dressings and is not only inconvenient for the patients and medical staff, but also economically disadvantageous. Wound healing materials should also provide a substrate for tissue regeneration and should be able to deliver active agents like drugs within a controlled manner during healing. These are, until today, difficult realisable requirements. Therefore new approaches concerning wound dressings are desired and nano nonwovens may find an answer to the above mentioned problems.

Some specific properties of nanofibre structures make them most suitable for use in wound dressings. The high porosity, well interconnected pores and high specific surface area, provide an excellent material for the absorption of fluids. In the meantime, the structures control the fluid drainage and prevent dehydration of the wounds by keeping them damp, without an accumulation of exudates under

© Woodhead Publishing Limited, 2011

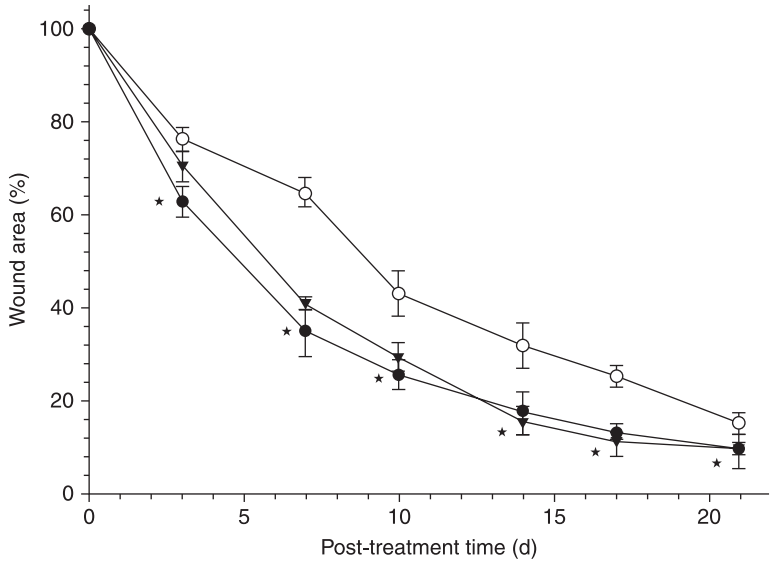
the coverings. This idea of maintaining moist wounds is believed to be beneficial for the healing process (Kumar, 2006). Moreover, because of the small pores, exogenous microorganisms are prevented from entering the wound and infections are avoided (Fang *et al*., 2008). Furthermore, the numerous pores assure the exchange of liquids and gases (with oxygen as most important gas) with the environment (Greiner and Wendorff, 2007). Because of the high level of surface area, also cell adhesion, spreading and proliferation are expected to be promoted by the use of nanofibrous structures (Min *et al*., 2004a). Experiments indeed show a higher level of cell adhesion and spreading on nanofibre structures (Min *et al*., 2004b; Noh *et al*., 2006).

Several polymers are being used to produce nanofibre wound dressings. Especially biodegradable polymers seem to be interesting in this field. A distinction is made between natural and synthetic polymers. Natural polymers typically show better interactions with human cells and low immunogenicity, both being favourable for wound healing. They are however difficult to process in electrospinning and the intrinsic variation in their properties is another disadvantage. Natural polymers are divided in proteins (such as collagen and silk fibroin) and polysaccharides (such as chitosan and cellulose) (Schiffman and Schauer, 2008). Synthetic polymers on the other hand, tend to have enhanced mechanical properties and are easier to engineer for specific applications but show less interaction with native cells. By combining natural and synthetic polymers, the advantages of both may deliver a superior wound dressing. Below, an overview of the most commonly used materials for wound dressings is given, without the intention of delivering a complete, exhaustive study on the polymers applied in wound dressing.

A natural polymer that is of interest for wound dressings is collagen as it is a natural ECM component of skin. By producing structures composed of collagen nanofibres, the three-dimensional network structure in native ECM is mimicked. In open wound tests on rats, researchers found that early-stage healing was faster compared to the control group that was treated with cotton gauze (Rho *et al*., 2006). Chitosan, a natural polysaccharide, shows haemostatic activity, non-toxicity, biodegradability and intrinsic antibacterial properties and is therefore considered as a promising wound dressing material (De Vrieze *et al*., 2007; Ignatova *et al*., 2006). When collagen and chitosan are combined by blending, a membrane promoting dermal and epidermal growth was generated which showed better results in wound healing compared to commercial gauzes, as presented in Fig. 24.3 (Chen *et al*., 2008). Also silk fibroin has been electrospun and has potential use as nanofibre wound dressing because of its biocompatibility and biodegradability. In addition, silk fibroin structures can be tailored to being well oxygen and water vapour permeable (Min *et al*., 2004a).

The most commonly known and applied synthetic polymers for medical use are synthetic polyesters like polyglycolic acid (PGA), polylactic acid (PLA), polycaprolactone (PCL) and their copolymers. These polymer types are approved

© Woodhead Publishing Limited, 2011



24.3 Wound area at different healing times of wounds treated with (o) commercial gauze, (▼) commercial collagen sponge and (•) collagen/chitosan nanofibrous membrane (Chen *et al.,* 2008).

by the U.S. Food and Drug Administration (FDA) to be used in medical applications. They degrade into non-toxic end products in timeframes – depending on various factors like the molecular structure, the molecular weight etc – varying between weeks and several months. PGA shows some interesting properties like biocompatibility and high strength but is not ideal to be used in wound dressing because of the fast degradation time (Dong *et al*., 2009). PCL and to a lesser degree PLA, show slower degradation rates and both possess similar properties as PGA. Therefore they are more appropriate candidates for wound-management material (You *et al*., 2005; Duan *et al*., 2007; van der Schueren *et al*., 2011).

Another promising synthetic polymer class is polyurethane. These polymers show some interesting characteristics like excellent barrier properties and oxygen permeability (Lamba *et al*., 1998). Polyurethane nanostructures are capable of exuding body fluid from the wound without desiccating the wound and without a build-up of water under the covering thanks to the controlled water loss through evaporation. Histological experiments on pigs show that the rate of epithelialisation when using electrospun polyurethane mats was increased compared to the rate when non nanofibre structures were used (Khil *et al*., 2003).

Also polyvinyl alcohol polymers (PVA) possess some properties like biocompatibility, chemical resistance, good mechanical properties and non-toxicity and they can consequently be used as wound covering material. PVA is however water-soluble which may give problems in a moisture environment such

© Woodhead Publishing Limited, 2011

as a wound area. This can be encountered by cross-linking induced by a heat treatment (Hong, 2006; Jia *et al*., 2007).

Several examples of combinations of natural and synthetic polymers are available in literature (Shalumon *et al*., 2010; Park *et al*., 2010). When the natural polymer collagen is combined with the synthetic PCL, the obtained hybrid structure promotes cell adhesion, proliferation and spreading of dermal fibroblasts, and thus enhances wound healing (Venugopal *et al*., 2006). By merging PLA and chitosan, the advantageous properties of polyesters and the antibacterial properties of chitosan are combined and a promising wound dressing material is produced (Ignatova *et al*., 2009). The natural polymer alginate possesses some promising properties for use in wound care like biocompatibility, biodegradability, non-toxicity and hydrophilicity. Electrospinning pure alginate is impossible but by blending the natural alginate with a synthetic biodegradable polymer like PVA or PEO (polyethylene oxide), an interesting material could be obtained (Lu *et al*., 2006, Safi *et al*., 2007).

There are several ways to provide nanostructures with biocidal properties and, in this way, decontaminate the invasion of bacteria and microorganisms. It is known that silver is the most toxic element to microorganisms and that silver ions therefore have a biocidal effect on a whole range of bacteria (Son *et al*., 2004; Lala *et al*., 2007). Thus, by incorporating silver in the nanofibres, the risk of infections is lowered significantly. Because of the large specific surface area of nanostructures, it is believed that the antimicrobial activity will be stronger on nanofibres than on conventional microfibers (Son *et al*., 2004). Moreover, electrospinning facilitates the production of such silver nanoparticle–polymer composite systems because the incorporation can be realised by adding silver nitrate or silver nanoparticles to the polymer solution before the start of the electrospinning process. The incorporation imposes no difficulties during the production process and the nanoparticles are evenly distributed along the obtained nanofibres (Jin *et al*., 2005; Jia *et al*., 2007) (see Fig. 24.3). When, for example, PVA is combined with silver nitrate, silver ions are released and provide a fast and constant antimicrobial activity to the wound area (Hong, 2006).

Besides silver, also iodine can offer biocidal activity (Mizukami and Yokoyama, 1996). Therefore polyvinylpyrrolidone (PVP)–iodine nanofibres, which release iodine gradually, were produced (Ignatova *et al*., 2007). Another way to realise antibacterial properties is by using antimicrobial polymers. Jeong *et al*., (2007) used for example modified polyurethane with quaternary ammonium groups – which are known to have disinfectant properties – to produce nanofibres by electrospinning. Also chitosan was quaternised to obtain better antibacterial properties (Ignatova *et al*., 2006).

Besides adding antimicrobial activity to the wound dressings, other components can be added to realise extra functionalities. Zinc chloride is added because of its antiphlogistic ability and because it can act as a nutrient agent for wounds (Moon and Crabtree, 2003). Tin oxide nanoparticles are used as soothing and odour-controlling agents (Hong *et al*., 2008).

© Woodhead Publishing Limited, 2011

For future industrial applications, the nanofibre structures will probably be produced continuously on a large scale, followed by the distribution and use on patients. An alternative process has however been developed by Smith and Reneker (2001) to directly electrospin a nonwoven structure on the skin by a small device (see Fig. 24.4).

24.4 Handheld device for the electrospinning of wound dressings (Greiner and Wendorff, 2007).

24.3.2 Drug release systems

As mentioned in Section 24.3.1, wound healing is a complex process in which various problems could occur, one of them being the development of infections. These infections prolong the healing process significantly and scars are more likely to be formed (Edwards and Harding, 2004). Drugs like antibiotics are used to treat the infections but oral ingestion can be inconvenient for the patients and can cause complications like renal and liver toxicity (Suzuki *et al*., 1998). Moreover, the functionality of the drugs can be lowered through intestinal transit (Yih and Al-Fandi, 2006). Therefore local application of the drugs is considered as beneficial (Noel *et al*., 2008). Such kind of local delivery systems are known as drug release systems and release drugs efficiently in medical therapy. Ideally, the drugs are used in the appropriate amount, at the infection site and for the duration of the infection. Because of the local delivery of the drugs, the risk of toxicity, associated with the traditional treatments, is minimised. Besides external application on wounds, also internal use is possible for example to prevent post-surgical adhesion (Kim *et al*., 2004).

© Woodhead Publishing Limited, 2011

Nanofibrous structures show some specific properties making them applicable in drug delivery systems. The production of nanofibrous structures is made straightforward and quite simple thanks to the electrospinning technique. The drug loading can proceed easily by adding the drugs to the polymer solution before the start of the process. Due to the high specific surface area, the release rate can reach high values (Zong *et al*., 2002). Moreover, nanofibres may help to deliver the drug efficiently because drugs are absorbed better into the body the smaller the dimensions of the carrier material (Huang *et al*., 2003). Furthermore, experiments show that the electrospinning process has no influence on the activity and behaviour of the incorporated drugs (Kim *et al*., 2004; Taepaiboon *et al*., 2006; Zong *et al*., 2002) and that the drugs are evenly distributed along the fibres (Luong-Van *et al*., 2006). Another advantage is that the obtained loaded nanofibre structures can be cut in any necessary form and thus easily provide a local delivery of drugs (Kenawy *et al*., 2002).

The polymers typically used in drug release devices, are generally similar to the ones used as wound dressing materials. Particularly biodegradable polymers are used such as PLA, PGA, PCL, PVA and PEO and their copolymers (Kenawy *et al*., 2002; Katti *et al*., 2004; Kenawy *et al*., 2007; Luong-Van *et al*., 2006; Zeng *et al*., 2003). The general principle of a drug delivery system consisting out of biodegradable polymers, is the release of incorporated drugs by the steady degradation of the surrounding polymer together with the diffusion of the drugs through the polymer structure. However also non-biodegradable polymers in which the drug release is only caused by diffusion, are used (Verreck *et al*., 2003).

Both hydrophobic and hydrophilic drugs can be incorporated in nanofibres, this being an advantage above other drug delivery systems such as hydrogels, which are mostly limited to hydrophilic drugs, and polymeric micelles, which are more suitable for hydrophobic drugs (Kim *et al*., 2004). Besides drugs, macromolecules like DNA, proteins and growth factors can be added. These agents are however water-soluble and entrapment and sustained release by conventional electrospinning is quite challenging. Luu *et al*. (2003) succeeded in adding DNA to biodegradable block copolymers but the DNA was located at the surface of the fibres which resulted in burst release. Modifications should be made to really entrap the DNA within the fibres and in this way, promote homogeneous release induced by polymer degradation. Also in the case of proteins, it remains difficult to eliminate an initial burst release (Kim *et al*., 2007).

Burst release is an often occurring situation in drug delivery systems. Sometimes, a burst release can be beneficial but generally, a homogeneous, constant release profile is desired. Many parameters influence the release kinetics of a nanofibre drug delivery system such as the type of polymers, the hydrophilicity and hydrophobicity of the polymers and incorporated drugs, the solubility of the polymers and drugs, the morphology of the nanostructures, the state of drug molecules in the electrospinning medium, etc. A major advantage of electrospun drug release systems is that the release profile and kinetics can be accurately

© Woodhead Publishing Limited, 2011

controlled by tailoring the morphology, porosity and composition of the nanostructures. In this way burst release can be minimised (Zeng *et al*., 2005a; Taepaiboon *et al*., 2006; Kim *et al*., 2004).

However, also the drug concentration influences the release profile, a higher concentration imposes a higher risk on burst release due to the enrichment of drugs on the nanofibre surface (Kim *et al*., 2004). To avoid this burst release, much attention must be paid to the solubility and compatibility of the drugs in the polymer–solvent system. When the drugs are insoluble, only a dispersion can be obtained and the drugs will be located on or near the surface of the nanofibres which results in a burst release (Zeng *et al*., 2005a).

Besides a proper choice of materials, other approaches are applied to prevent burst release. A covalent conjugation of the drugs to the polymer avoids a high initial drug delivery (Jiang *et al*., 2004). Coating the nanofibres with a polymer shell is another approach to control the release profile (Zeng *et al*., 2005b). To further improve the release, coaxial electrospinning was introduced (Huang *et al*., 2005). This is a simple process in which a high loading capacity can be obtained and in which the release profile can be easily controlled by changing the feed rate of the shell and core capillaries (Jiang *et al*., 2005; Jiang *et al*., 2006).

Several studies attempted to predict the effect of drug loading on the nanofibre diameter and morphology. Mostly, an effect on the average fibre diameters is found and both an increase and a decrease in diameters are noticed (Katti *et al*., 2004; Kim *et al*., 2004). In a number of drug–polymer combinations the morphology of the structures is not influenced by the drug loading while other drug–polymer systems undergo changes. These results indicate that the effects depend on the drug type and the applied polymer. In conclusion, both the effect of the incorporation of the drugs on the nanofibre morphology and diameter as well as the obtained release profile should be studied individually for each combination of polymers and drugs.

24.3.3 Tissue engineering

Tissue engineering is described as an interdisciplinary field that applies the principles of engineering and life science to the development of biological substitutes that restore, maintain or improve tissue function (Langer and Vacanti, 1993). A tissue engineered scaffold is a structure that replaces the natural extracellular matrix (ECM) until host cells can repopulate and resynthetise a new natural matrix (Li *et al*., 2002). To fulfil the desired biological function, morphological similarity with the native tissue is important (Zhang *et al*., 2005b). Scaffolds should also possess a high porosity since this is important for cell proliferation. Also an appropriate pore size distribution and a high surface area to provide sufficient space for cell attachment are necessary. Generally, the scaffolds must be biodegradable with a degradation rate similar to the rate of the new natural tissue formation. Biocompatibility and non-toxicity are other quite

© Woodhead Publishing Limited, 2011

logical conditions since the tissues are used inside the body. When the scaffolds are applied to treat large tissue defects, they should also enable blood vessel ingrowth (Shin *et al*., 2004). Finally, good mechanical properties matching the characteristics of the damaged tissue and structural integrity need to be present.

The materials and structures that are so far used as scaffolds are very diverse. Foams, gels, powders and membranes made out of a variety of materials, are tested as potential tissue engineering material. Their efficiency is however limited partially due to the micrometre size diameters in comparison with the nanometre size of native tissues. Because of this, cells can not grow in the depth of the scaffold and a three dimensional structure is unable to form (Lee *et al*., 2005).

The requirements for scaffolds are closely related to the properties of nanofibrous structures so these materials may have a good potential in tissue engineering. Moreover, the electrospinning process is capable of producing a complex, seamless and three-dimensional structure which is similar to the ECM. Another advantage is that, because of the small diameters, human cells can attach and organise well around the fibres (Huang *et al*., 2003). Additionally, cells are able to infiltrate and grow inside the scaffold (Zhang *et al*., 2005a). To allow an even better migration of the cells, micro and nanofibres can be combined (Tuzlakkoglu *et al*., 2005). The high porosity also promotes nutrient and waste transport which is beneficial for the healing process (Shin *et al*., 2004). Besides being used as a soft tissue, electrospun nanofibres can also be deposited on a hard tissue prosthetic device and serve as an interphase between the prosthetic device and the host tissue. As a result, the stiffness mismatch between the hard device and the native tissue is reduced and the device failure is prevented (Buchko *et al*., 1999).

The polymer types used in tissue engineering are not very different from the ones used for wound dressings and drug delivery. Both natural and synthetic and biodegradable and non-biodegradable polymers are applied. Again biodegradable polyesters such as PGA, PLA and PCL are the most commonly used. Despite the fact that natural polymers show excellent biocompatibility and cell adhesion, their mechanical strength is mostly too low to be used *in vitro*. Therefore, synthetic polymers are more widely studied for tissue engineering. To improve the biocompatibility of these synthetic polymers and consequently assist the repair of damaged tissue, specific components are adsorbed onto their surface (Yoshimoto *et al*., 2003). A variety of cells such as proteins, fibroblasts, stem cells etc are seeded on the structures to support the recovery (Riboldi *et al*., 2005). This seeding can proceed more efficiently compared to conventional tissue engineering systems because of the high specific surface area and nanoscale roughness (Greiner and Wendorff, 2007). Another approach to solve this shortcoming is blending synthetic and natural polymers or modifying the polymer surface by grafting certain components (Venugopal *et al*., 2005; Ma *et al*., 2005b).

© Woodhead Publishing Limited, 2011

Nanofibrous structures could be used for engineering a whole range of tissues like muscles, bones, cartilages, vessels, etc:

- Muscle cells adhere and proliferate well on membranes consisting of different types of polymers and different polymer blends. Studies on the cell behaviour of muscle cells in a PLA/PCL polymer blend, showed that not only cell attachment and proliferation was promoted, but that the cells also maintained their specific phenotype which indicates their biological function within the scaffold (Mo *et al*., 2004).
- PCL is the most common polymer used for bone tissue engineering mainly because of its slow degradation process and its good mechanical properties (Li *et al*., 2005a). Calcium carbonate can be added to promote the growing process of bone cells (Fujihara *et al*., 2005).
- Because the repair of injured cartilage is currently still difficult, nanofibre scaffolds are studied to cover this. Collagen nanofibres showed good compatibility with the cells present in cartilage and can be used in cartilage-mimicking scaffolds (Matthews and Boland, 2003).
- Blood vessels, especially the small-diameter ones, are other crucial tissues difficult to replace when damaged. The fabrication of vascular grafts should be controlled accurately because of the diversity in size, mechanical and biochemical properties, cellular content and ultrastructural organisation of blood vessels (Agarwal *et al*., 2008). By combining different polymers, both synthetic and natural, it is possible to tailor the mechanical and antithrombogenic properties of the vascular scaffolds. Thus, the configuration, function and flexibility of native blood vessels can be mimicked (Lee *et al*., 2007; Stitzel *et al*., 2006). Grafting a synthetic structure with a natural polymer like gelatine, improves the growth and spreading of the vessel cells. Alignment of the nanofibres serves to the orientation of the cells, which is in agreement with native blood vessels (Ma *et al*., 2005).

Above only a few examples of human tissues are mentioned, actually a whole range of other tissues can be mimicked by nanofibrous structures.

24.4 Future trends

24.4.1 Polymer modifications

As already mentioned before, it is possible to obtain different and new material properties by combining different polymers. These combinations can be realised by copolymerisation or blending. A major advantage of this approach is that the resulting properties can be tailored by adjusting the component ratios. Blending is more widely applicable because it is not limited by suitable synthetic schemes (Xie *et al*., 2008). In conclusion, by choosing the proper combinations of polymers, the performance of the nanofibrous structures can reach the optimum conditions for medical use.

© Woodhead Publishing Limited, 2011

24.4.2 Process modifications

To further optimise the characteristics of the nanofibrous structures, innovations in the electrospinning technique have been developed. Core-shell electrospinning is not only valuable to produce drug release devices, the shell also protects the material of the core during the electrospinning process which enables the incorporation of living cells (Townsend-Nicholson and Jayasinghe, 2006). Moreover, even hollow fibres can be produced in this way (Liang *et al*., 2007).

To obtain the desired and natural anisotropy of certain cells, aligned nanofibres are sometimes necessary. A rotating wheel can therefore be used instead of a static collector plate (Corey *et al*., 2007; Lee *et al*., 2005a). In order to optimise the transport of components through a nanofibrous scaffold, a structure with dual porosity is developed. Salts and nanoparticles, that enhance the mechanical properties, are incorporated into the structure that is afterwards treated using a salt leaching/gas forming method. Consequently, a nonwoven consisting of small pores, originating from the interstices between the nanofibres, and larger pores, arising from the after treatment, is produced (Lee *et al*., 2005b).

24.4.3 Post-treatments

After fabrication of the nanofibrous structures, modifications of the surface can further improve the biological properties while maintaining the advantages of nanofibrous structures. These modifications are generally realised by grafting the surface with bioactive components (Chua *et al*., 2005; Ma *et al*., 2005a). Besides grafting, coatings and plasma treatments modify the characteristics of the nanofibrous surfaces in order to generate the desired properties (Park *et al*., 2007).

24.5 Sources of further information and advice

Further literature and information about nanofibres in general can be found in the reference books from Ramakrishna *et al*. (2005) and Brown and Stevens (2007). For technical and industrial information the website of Fibroniq can be checked, which is a consortium of laboratories of Ghent University that merge their expertise in the development of electrospinning technology and nanofibrous structures and in the development of prototype products using nanofibrous structures (http://www.fibroniq.be/).

24.6 References

Agarwal S, Wendorff J H and Greiner A (2008). Use of electrospinning technique for biomedical applications, *Polymer*, 49, 5603–5621.

Brown P J and Stevens K (2007). *Nanofibers and Nanotechnology in Textiles*, Woodhead Publishing Ltd, UK.

© Woodhead Publishing Limited, 2011

Buchko C J, Chen L C, Chen Y and Martin D C (1999). Processing and microstructural characterization of porous biocompatible protein polymer thin films, *Polymer*, 40, 7397–7407.

Chen J-P, Chang G-Y and Chen J-K (2008). Electrospun collagen/chitosan nanofibrous membrane as wound dressing, *Colloids Surf A*, 313/4, 183–188.

Chua K-N, Lim W-S, Zhang P, Lu H, Wen J, *et al.* (2005). Stable immobilization of rat hepatocyte spheroids on galactosylated nanofiber scaffold, *Biomaterials*, 26, 2537–2547.

Corey J M, Lin D Y, Mycek K B, Chen Q, Samuel S, *et al.* (2007). Aligned electrospun nanofibers specify the direction of dorsal root ganglia neurite growth, *J Biomed Mater Res Part A*, 83A, 636–645.

De Vrieze S, Westbroek P, Van Camp T and Van Langenhove L (2007). Electrospinning of chitosan nanofibrous structures: feasibility study, *J Mater Sci*, 42, 8029–8034.

Dong Y, Liao S, Ngiam M, Chan C K and Ramakrishna S (2009). Degradation Behaviors of Electrospun Resorbable Polyester Nanofibers, *Tissue Eng Part B: Rev*, 15, 333–351.

Duan Y-Y, Jia J, Wang S-H, Yan W, Jin L and Wang Z-Y (2007). Preparation of antimicrobial poly(ε-caprolactone) electrospun nanofibers containing silver-loaded zirconium phosphate nanoparticles, *J Appl Polym Sci*, 106, 1208–1214.

Edwards R and Harding K G (2004). Bacteria and wound healing, *Curr Opin Infect Disease*, 17, 91–96.

Ellison C J, Phatak A, Giles D W, Macosko C W and Bates F S (2007). Melt blown nanofibers: Fiber diameter distributions and onset of fiber breakup, *Polymer*, 48, 3306–3316.

Fang J, Niu H, Lin T and Wang X (2008). Applications of electrospun nanofiber*s*, *Chin Sci Bull*, 53, 2265–2286.

Feng X, Yang G, Xu Q, Hou W and Zhu J-J (2006). Self-Assembly of polyaniline/Au composites: From nanotubes to nanofibers, *Macromol Rapid Commun*, 27, 31–36.

Fujihara K, Kotaki M and Ramakrishna S (2005). Guided bone regeneration membrane made of polycaprolactone/calcium carbonate composite nano-fibers, *Biomaterials*, 26, 4139–4147.

Greiner A and Wendorff J H (2007). Electrospinning: A fascinating method for the preparation of ultrathin fibers, *Angew Chem Int Ed*, 46, 5670–5703.

Hong K H (2006). Preparation and Properties of Electrospun Poly(vinyl alcohol)/Silver Fiber Web as Wound Dressings, *Polym Eng Sci*, 47, 43–49.

Hong Y, Li Y, Zhuang X, Chen X and Jing X (2008). Electrospinning of multicomponent ultrathin fibrous nonwovens for semi-occlusive wound dressings, *J Biomed Mater Res Part A*, 89A, 345–354.

Huang Z-M, Zhang Y-Z, Kotaki M and Ramakrishna S (2003). A review on polymer nanofibers by electrospinning and their applications in nanocomposites, *Composite Sci Technol*, 63, 2223–2253.

Huang Z-M, He C-H, Yang A, Zhang Y, Han X-J, *et al.* (2005). Encapsulating drugs in biodegradable ultrafine fibers through co-axial electrospinning, *J Biomed Mater Res Part A*, 77A, 169–179.

Ignatova M, Starbova K, Markova N, Manolova N and Rashkov I (2006). Electrospun nano-fibre mats with antibacterial properties from quaternised chitosan and poly(vinyl alcohol). *Carbohydr Res*, 341, 2098–2107.

Ignatova M, Manolova N and Rashkov I (2007). Electrospinning of poly(vinyl pyrrolidone)-iodine complex and poly(ethylene oxide)/poly(vinyl pyrrolidone) iodine complex - a prospective route to antimicrobial wound dressing materials, *Eur Polym J*, 43, 1609–1623.

© Woodhead Publishing Limited, 2011

Ignatova M, Manolova N, Markova N and Rashkov I (2009). Electrospun non-woven nanofibrous hybrid mats based on Chitosan and PLA for wound-dressing applications, *Macromol Biosci*, 9, 102–111.

Ikegame M, Tajima K and Aida T (2003). Template Synthesis of Polypyrrole Nanofibers Insulated within One-Dimensional Silicate Channels: Hexagonal versus Lamellar for Recombination of Polarons into Bipolarons, *Angew Chem*, 115, 2204–2207.

Jeong E H, Yang J and Youk J H (2007). Preparation of polyurethane cationomer nanofiber mats for use in antimicrobial nanofilter applications, *Mater Lett*, 61, 3991–3994.

Jia J, Duan Y-Y, Wang S-H, Zhang S-F and Wang Z-Y (2007). Preparation and characterization of antibacterial silver-containing nanofibers for wound dressing applications, *J US-China Med Sci*, 4, 52–54.

Jiang H, Fang D, Hsiao B, Chu B and Chen W (2004). Preparation and characterization of ibuprofen-loaded poly(lactide-co-glycolide)/poly(ethylene glycol)-g-chitosan electrospun membranes, *J Biomater Sci Polym E*d, 15, 279–296.

Jiang H, Hu Y, Li Y, Zhao P, Zhu K and Chen W (2005). A facile technique to prepare biodegradable coaxial electrospun nanofibers for controlled release of bioactive agents, *J Controlled Release*, 108, 237–243.

Jiang H, Hu Y, Zhao P, Li Y and Zhu K (2006). Modulation of protein release from biodegradable core–shell structured fibers prepared by coaxial electrospinning, *J Biomed Mater Res Part B*, 79, 50–57.

Jin W-J, Lee H K, Jeong E H, Park W H and Youk J H (2005). Preparation of polymer nanofibers containing silver nanoparticles by using poly(N-vinylpyrrolidone), *Macromol Rapid Commun*, 26, 1903–1907.

Katti D S, Robinson K W, Ko F K and Laurencin C T (2004). Bioresorbable nanofiber-based systems for wound healing and drug delivery: Optimization of fabrication parameters, *J Biomed Mater Res*, 70B, 286–296.

Kenawy E-R, Bowlin G L, Mansfield K, Layman J, Simpson D G, *et al.* (2002). Release of tetracycline hydrochloride from electrospun poly(ethylene-co-vinylacetate). poly(lactic acid) and a blend, *J Controlled Release*, 81, 57–64.

Kenawy E-R, Abdel-Hay F-I, El-Newehy M H and Wnek G E (2007). Controlled release of ketoprofen from electrospun poly(vinyl alcohol) nanofibers, *Mater Sci Eng A*, 459, 390–396.

Khil M-S, Cha D-I, Kim H-Y, Kim I-S and Bhattarai N (2003). Electrospun nanofibrous polyurethane membrane as wound dressing, *J Biomed Mater Res Part B*, 67B, 675–679.

Kim K, Luu Y K, Chang C, Fang D, Hsiao B S, Chu B and Hadjiargyrou M (2004). Incorporation and controlled release of a hydrophilic antibiotic using poly(lactide-co-glycolide)-based electrospun nanofibrous scaffolds, *J Controlled Release*, 98, 47–56.

Kim T G, Lee D S and Park T G (2007). Controlled protein release from electrospun biodegradable fiber mesh composed of poly(?-caprolactone) and poly(ethylene oxide), *Int J Pharm*, 338, 276–283.

Kumar C (2006). *Tissue, Cell and Organ Engineering*, Weinheim, Wiley-VCH.

Lala N L, Ramaseshan R, Bojun L, Sundarrajan S, Barhate R S, *et al.* (2007). Fabrication of Nanofibers With Antimicrobial Functionality Used as Filters: Protection Against Bacterial Contaminants, *Biotechnol Bioeng*, 97, 1357–1365.

Lamba N, Woodhouse K, Cooper S (1998). *Polyurethane in Biomedical Applications*, CRC Press, New York.

Langer R and Vacanti JP (1993). Tissue engineering, *Science*, 260, 920–926.

© Woodhead Publishing Limited, 2011

Larrondo L and Manley R St J (2003). Electrostatic fiber spinning from polymer melts. I. Experimental observations on fiber formation and properties, *J Polym Sci: Polym Phys Ed*, 19, 909–992.

Lee C H, Shin H J, Cho I H, Kang J-M, Kim I A, *et al.* (2005a). Nanofiber alignment and direction of mechanical strain affect the ECM production of human ACL fibroblast, *Biomaterials*, 26, 1261–1270.

Lee Y H, Lee J H, An I-G, Kim C, Lee D S, *et al.* (2005b). Electrospun dual-porosity structure and biodegradation morphology of Montmorillonite reinforced PLLA nanocomposite scaffolds, *Biomaterials*, 26, 3165–3172.

Lee S J, Joo J J, Lim G J, Atala A and Stitzel J (2007). In vitro evaluation of electrospun nanofiber scaffolds for vascular graft application, *J Biomed Mater Res Part A*, 83A, 999–1008.

Li W-J, Laurencin C T, Caterson E J, Tuan R S and Ko F K (2002). Electrospun nanofibrous structure: A novel scaffold for tissue engineering, *J Biomed Mater Res Part A*, 60, 613–621.

Li D and Xia Y (2004). Electrospinning of nanofibers: Reinventing the wheel?, *Adv Mater*, 16, 1151–1170.

Li W-J, Tuli R, Huang X, Laquerriere P and Tuan R S (2005a). Multilineage differentiation of human mesenchymal stem cells in a three-dimensional nanofibrous scaffold, *Biomaterials*, 26, 5158–5166.

Li H, Ke Y and Hu Y (2005b). Polymer Nanofibers Prepared by Template Melt Extrusion, *J Appl Polym Sci*, 99, 1018–1023.

Liang D, Hsiao B S and Chu B (2007). Functional electrospun nanofibrous scaffolds for biomedical applications, *Adv Drug Delivery Rev*, 59, 1392–1412.

Lu J-W, Zhu Y-L, Guo Z-X, Hu P and Yu J (2006). Electrospinning of sodium alginate with poly(ethylene oxide), *Polymer*, 47, 8026–8031.

Luong-Van E, Grøndahl L, Chua K N, Leong K W, Nurcombe V and Cool S M (2006). Controlled release of heparin from poly(?-caprolactone) electrospun fibers, *Biomaterials*, 27, 2042–2050.

Luu Y K, Kim K, Hsiao B S, Chu B and Hadjiargyrou M (2003). Development of a nanostructured DNA delivery scaffold via electrospinning of PLGA and PLA–PEG block copolymers, *J Controlled Release*, 89, 341–353.

Lyons J, Li C, Ko F (2004). Melt-electrospinning part I: processing parameters and geometric properties, *Polymer*, 45, 7597–7603.

Ma P X and Zhang R (1999). Synthetic nano-scale fibrous extracellular matrix, *J Biomed Mater Res Part A*, 46, 60–72.

Ma Z, Kotaki M, Yong T, He W and Ramakrishna S (2005a). Surface engineering of electrospun polyethylene terephthalate (PET) nanofibers towards development of a new material for blood vessel engineering, *Biomaterials*, 26, 2527–2536.

Ma Z, He M, Yong T and Ramakrishna S (2005b). Grafting of gelatin on electrospun poly(caprolactone) nanofibers to improve endothelial cell spreading and proliferation and to control cell orientation, *Tissue Eng*, 11, 1149–1158.

Marler J J, Upton J, Langer R and Vacanti J P (1998). Transplantation of cells in matrixes for tissue regeneration, *Adv Drug Delivery Rev*, 33, 165–182.

Martin C R (1996). Membrane-based synthesis of nanomaterials, *Chem Mate*r, 8, 1739–1746.

Matthews A and Boland E D (2003). Electrospinning of collagen type II: A feasibility study, *J Bioactive Compatible Polym*, 18, 125–134.

Min B-M, Lee G, Kim S H, Nam Y S, Lee T S and Park W H (2004a). Electrospinning of silk fibroin nanofibers and its effect on the adhesion and spreading of normal human keratinocytes and fibroblasts in vitro, *Biomaterials*, 25, 1289–1297.

© Woodhead Publishing Limited, 2011

Min B-M, Jeong L, Nam Y S, Kim J-M, Kim J Y and Park W H (2004b). Formation of silk fibroin matrices with different texture and its cellular response to normal human keratinocytes, *Int J Biol Macromol*, 34, 223–230.

Mizukami Y and Yokoyama T (1996). A study on the bactericidal activity of povidone-iodine, *Med Electron Microsc*, 26, 111–115.

Mo X M, Xu C Y, Kotaki M and Ramakrishna S (2004). Electrospun P(LLA-CL) nanofiber: a biomimetic extracellular matrix for smooth muscle cell and endothelial cell proliferation, *Biomaterials*, 25, 1883–1890.

Moon C H and Crabtree T G (2003). New Wound Dressing Techniques to Accelerate Healing, *Curr Treat Option Infect Disease*, 5, 251–260.

Nakata K, Fujii K, Ohkoshi Y, Gotoh Y, Nagura M, *et al*. (2007). Poly(ethylene terephthalate) nanofibers made by sea–island-type conjugated melt spinning and laser-heated flow drawing, *Macromol Rapid Commun*, 28, 792–795.

Noel S P, Courtney H, Bumgardner J D and Haggard W O (2008). Chitosan films, A potential local drug delivery system for antibiotics, *Clin Orthopaed Relate Res*, 466, 1377–1382.

Noh H K, Lee S W, Kim J-M, Oh J-E, Kim K-H, Chung C-P, *et al*. (2006). Electrospinning of chitin nanofibers: Degradation behavior and cellular response to normal human keratinocytes and fibroblasts, *Biomaterials*, 27, 3934–3944.

Ondarcuhu R and Joachim C (1998). Drawing a single nanofibre over hundreds of microns, *Europhys Lett*, 42, 215–220.

Park K, Ju Y M, Son J S, Ahn K-D and Han D K (2007). Surface modification of biodegradable electrospun nanofiber scaffolds and their interaction with fibroblasts, *J Biomater Sci Polym Ed*, 18, 369–382.

Park S A, Park K E and Kim W (2010). Preparation of sodium alginate/poly(ethylene oxide) blend nanofibers with lecithin, *Macromol Res,* 18, 891–896.

Ramakrishna S, Fujihara K, Teo W-E, Lim T-C and Ma Z (2005). *An introduction to electrospinning and nanofibers*, World Scientific Publishing, Singapore.

Rho K S, Jeong L, Lee G, Seo B-M, Park J Y, *et al*. (2006). Electrospinning of collagen nanofibers: Effects on the behavior of normal human keratinocytes and early-stage wound healing, *Biomaterials*, 27, 1452–1461.

Riboldi S A, Sampaolesi M, Neuenschwander P, Cossu G and Mantero S (2005). Electrospun degradable polyesterurethane membranes: potential scaffolds for skeletal muscle tissue engineering, *Biomaterials*, 26, 4606–4615.

Safi S, Morshed M, Ravandi S A H and Ghiaci M (2007). Study of Electrospinning of Sodium Alginate, Blended Solutions of Sodium Alginate/Poly(vinyl alcohol) and Sodium Alginate/Poly(ethylene oxide), *J Appl Polym Sci*, 104, 3245–3255.

Schiffman J D and Schauer C L (2008). A review: Electrospinning of biopolymer nanofibers and their applications, *Polym Rev*, 48, 317–352.

Shalumon K T, Anulekha K H, Girish C M, Prasanth R, Nair S V and Jayakumar R (2010). Single step electrospinning of chitosan/poly(caprolactone) nanofibers using formic acid/acetone solvent mixture, *Carbohyd Polym*, 80, 413–419.

Shin M, Yoshimoto H and Vacanti J P (2004). In vivo bone tissue engineering using mesenchymal stem cells on a novel electrospun nanofibrous scaffold, *Tissue Eng*, 10, 33–41.

Smith D and Reneker D H, PCT/US00/27737, 2001.

Son W K, Youk J H, Lee T S and Park W H (2004). Preparation of antimicrobial ultrafine cellulose acetate fibers with silver nanoparticles, *Macromol Rapid Commun*, 25, 1632–1637.

© Woodhead Publishing Limited, 2011

Stitzel J, Liu J, Lee S J, Komura M, Berry J, *et al*. (2006). Controlled fabrication of a biological vascular substitute, *Biomaterials*, 27, 1088–1094.

Suzuki Y, Tanihara M, Nishimura Y, Suzuki K, Kakimaru Y and Shimizu Y (1998). A new drug delivery system with controlled release of antibiotic only in the presence of infection, *J Biomed Mater Res*, 42, 112–116.

Taepaiboon P, Rungsardthong U and Supaphol P (2006). Drug-loaded electrospun mats of poly(vinyl alcohol) fibres and their release characteristics of four model drugs, *Nanotechnology*, 17, 2317–2329.

Townsend-Nicholson A and Jayasinghe S N (2006). Cell electrospinning: A unique biotechnique for encapsulating living organisms for generating active biological microthreads/scaffolds, *Biomacromolecules*, 7, 3364–3369.

Tuzlakkoglu K, Bolgen N, Salgado A J, Gomes M E, Piskin E and Reis R L (2005). Nano- and micro-fiber combined scaffolds: A new architecture for bone tissue engineering, *J Mater Sci: Mater Med*, 16, 1099–1104.

Van der Schueren L, De Schoenmaker B, Kalaoglu O I and De Clerk K (2011). An alternative solvent system for the steady state electrospinning of polycaprolactone, *Eur Polym J*, 47, 1256–1263.

van de Witte P, Dijkstra P J, van den Berg J W A and Feijen J (1996). Phase separation processes in polymer solutions in relation to membrane formation, *J Membr Sci*, 117, 1–31.

Venugopal J, Zhang Y and Ramakrishna S (2005). Fabrication of modified and functionalized polycaprolactone nanofibre scaffolds for vascular tissue engineering, *Nanotechnology*, 16, 2138–2142.

Venugopal J, Zhang Y and Ramakrishna S (2006). In vitro culture of human dermal fibroblasts on electrospun polycaprolactone collagen nanofibrous membrane, *Artif Organs*, 30, 440–446.

Verreck G, Chun I, Rosenblatt J, Peeters J, Van Dijck A, *et al*. (2003). Incorporation of drugs in an amorphous state into electrospun nanofibers composed of a water-insoluble, nonbiodegradable polymer, *J Controlled Release*, 92, 349–360.

Whitesides G M and Grzybowski B (2002). Self-assembly at all scales, *Science*, 295, 2418–2421.

Xie J, Li X and Xia Y (2008). Putting electrospun nanofibers to work for biomedical research, *Macromol Rapid Commun*, 29, 1775–1792.

Yih T C and Al-Fandi M (2006). Engineered nanoparticles as precise drug delivery systems, *J Cell Biochem*, 97, 1184–1190.

Yoshimoto H, Shin Y M, Terai H and Vacanti J P (2003). A biodegradable nanofiber scaffold by electrospinning and its potential for bone tissue engineering, *Biomaterials*, 24, 2077–2082.

You Y, Min B-M, Lee S J, Lee T S and Park W H (2005). In Vitro degradation behavior of electrospun polyglycolide, polylactide, and poly(lactide-co-glycolide), *J Appl Polym Sci*, 95, 193–200.

Zeng J, Xu X, Chen X, Liang Q, Bian X, *et al*. (2003). Biodegradable electrospun fibers for drug delivery, *J Controlled Release*, 92, 227–231.

Zeng J, Yang L, Liang Q, Zhang X, Guan H, *et al*. (2005a). Influence of the drug compatibility with polymer solution on the release kinetics of electrospun fiber formulation, *J Controlled Release*, 105, 43–51.

Zeng J, Aigner A, Czubayko F, Kissel T, Wendorff J H and Greiner A (2005b). Poly(vinyl alcohol) nanofibers by electrospinning as a protein delivery system and the retardation of enzyme release by additional polymer coatings, *Biomacromolecules*, 6, 1484–1488.

© Woodhead Publishing Limited, 2011

Zhang Y, Ouyang H, Lim C T, Ramakrishna S and Huang Z-M (2005a). Electrospinning of Gelatin Fibers and Gelatin/PCL Composite Fibrous Scaffolds, *J Biomed Mater Res Part B*, 72B, 156–165.

Zhang Y, Lim C T, Ramakrishna S and Huang Z-M (2005b). Recent development of polymer nanofibers for biomedical and biotechnological application*s*, *J Mater Sci: Mater Med*, 16, 933–946.

Zhou H, Green T B and Joo Y L (2006). The thermal effects on electrospinning of polylactic acid melts, *Polymer*, 47, 7497–7505.

Zong X, Kim K, Fang D, Ran S, Hsiao B S and Chu B (2002). Structure and process relationship of electrospun bioabsorbable nanofiber membranes, *Polymer*, 43, 4403–4412.

© Woodhead Publishing Limited, 2011

Index

AATCC 42, 90
AATCC 100, 395
AATCC 127, 87, 90
AATCC 100-2004, 344
AATCC 112-1998, 276
AATCC 147-2004, 344
AATCC Test Method 100, 343
AATCC Test Method 147, 343
absorbent hygiene products *see* absorbent products
absorbent products
  consumer needs, 319–21
    adult incontinence, 320
    baby diapers, 319–20
    feminine hygiene, 320–1
  future trends, 330–3
  key issues, 319–26
    diaper rash development, 322
    hygiene implications, 324–5
    skin protection properties, 321–4
  personal health care and hygiene, 316–33
    application, 329–30
  testing, 325–9
    clinical properties, 328
    consumer testing, 328
    developmental stages in a baby, 329
    device to measure absorption time, 326
    rewet measurement schematic, 327
    technical properties, 325–8
  types, 316–19
    adult incontinence products, 318
    baby diapers, 317–18
    diaper components, 317
    feminine hygiene products, 318–19
Absorbex, 10
absorption time, 326–7
Acinetobacter baumannii, 310–11
acquired resistance, 302–3
acquisition distribution layers (ADL), 114
Acticoat, 345
Actisorb, 408
Actisorb Plus, 50, 406
Actisorb Silver, 407
Actisorb Silver 220, 50
Acturel, 210
acute wounds, 40
adult incontinence, 320
adult incontinence products, 318
advanced therapy medicinal products, 148
AEGIS AEM 5772/5, 409
AGA-100, 45–6
agar diffusion test, 343
air permeability, 207
air plethysmography, 54
Alceru, 284
alginate, 5, 17–18
alkylbenzenesulfonate, 371, 372
allergies, 267–78
  main types caused by textiles, 268–70
  medical textile applications, 276–8
  testing for allergenic substance, 275–6
    disperse dyes, 275–6
    formaldehyde, 276
    nickel, 275
  types, 267–8
  ways to minimise and avoid allergies caused by textiles, 270–5
    criteria applied for OEKO-TEX STANDARD 100 certification, 272–3
    dyestuffs classified to be allergenic, 274
    Oeko-Tex Standard 100 label, 271
alpha sepilolite, 408
American Hospital Association agreement, 82
American Society for Testing and Materials, 150
American surgeon report, 98
Americos Industries Inc., 346
Amonton's law, 257
Ankle-to-brachial Blood Pressure Index (ABPI), 53–4
ANSI/AAMI PB70-2003, 89–90
anti-adhesive wound dressings, 309–10
'antibacterial resistome,' 303
antibacterial wound care dressings, 345
antimicrobial efficacy tests, 395–6

© Woodhead Publishing Limited, 2011

antimicrobial textiles, 337–9
antimicrobial wound dressings, 309
Aorfix, 139
aryl nitrene, 351–2
Ascophyllum nodosum, 286
Association for the Advancement of Medical Instrumentation, 89–90
ASTM C 518, 212
ASTM D 1518, 212
ASTM E 96, 212
ASTM E 2149, 396
ASTM E2149-10, 343
ASTM E 96 Procedure BW, 212
ASTM F23, 88
ASTM F1670, 88–9, 90
ASTM F1671, 88–9, 90
ASTM F 1868, 212
ASTM F 2298, 213
ATCC No. 6538, 344
atomic force microscopy, 183
atopic dermatitis, 262, 280
  age-related variation in clinical characteristics, 281
  antibacterial activity against *Staphylococcus aureus* of different fabrics, 289
  antifungal activity against *Candida albicans* of different fabrics, 288
  approaches for therapy and prevention, 280–90
  capability of tested fabrics to scavange ROS and RNS, 290
  Lyocell fibres for antimicrobial therapy, 284–6
    Lyocell process, 285
  Malassezia spp and *Candida* spp., 282
  role of microbial infections, 281–3
  SeaCell textiles, 286–9
    SEM picture of fibres and assessment of cryogenic breaks of fibres, 287
  skin barrier function and increased sensitivity to irritants, 283
atopic eczema *see* atopic dermatitis

baby diapers, 317–18, 319–20
bacterial cellulose, 19
bacterial colonisation, 23
bandages, 238–9
  see also compression bandages
bed sore *see* decubitus ulcer
bedding, 239–40, 261–2
behind-the-knee method, 257–8
beta-lactams, 301
bio-catalytic textiles, 341–2
bio-functional textiles, 336–54
  applications, 344–6
    antibacterial wound care dressings, 345
    cosmetic textiles, 346
    mosquito repellent garments, 344–5
  bio-functional effects and safety evaluation, 343–4
  future trends, 353–4
  manufacturing, 346–53
    bio-functional additives incorporation, 346–8
    chemical method, 351–3
    coating, 348–50
    grafting acyclic halamine moieties to polypropylene, 347
    surface modification, 350–1
    thermoplastic semi-interpenetrating network formation, 350
  non-apparel products, 340–3
    antimicrobial function, 340
    bio-catalytic textiles, 341–2
    bio-sensing textiles, 340–1
    textiles as carriers for drug/protein/nutrient delivery, 342–3
  types, 336–43
Bio-Seed-C, 146
bio-sensing textiles, 340–1
bio-tribometer, 256–7
bioartificial liver support systems, 147
bioconjugation, 180–2
biodegradable aliphatic polyester, 7
biofunctional textiles
  based on cellulose and their approaches for atopic eczema therapy and prevention, 280–90
  future trends, 289–90
  Lyocell fibres for antimicrobial therapy, 284–6
  role of microbial infections in atopic dermatitis, 281–3
  SeaCell textiles for antimicrobial therapy, 286–9
  skin barrier function and increased sensitivity to irritants, 283
Biological Evaluation of Medical Devices, 149–50
biomaterials
  and modern textiles for healthcare, 3–29
    contacting behaviour and transmission phenomenon, 14–16
    information sources and advice, 29
    medical textile products properties, 9–14
    role, 4–5
    stability and compactness engineering, medical textile systems, 16–18
    types and medical applications, 5–9
  future trends, 22–9
    finishing using nanotechnology, 27
    scientific strategies, nanosystems and smart products, 26–9
    tissue engineering concepts, 24–6
    trends and challenges new products and applications, 22–3
  research examples and product development, 18–22
    modern textile architectures and specialised materials, 21–2
    visible fibre to molecular shape, 18–21

© Woodhead Publishing Limited, 2011

Biomechanical Tissue Characterisation System, 254
BioSAP, 512
biosensors, 340–1
biphasic amyloidosis, 259
Black Death, 298
black heel, 252–3
blisters, 251
BPI Hohenstein, 435
breathability, 235
British Pharmacopoeia, 66
BS 5058, 233
BS 7505:19956, 490
bubonic plague, 298
burst release, 556–7

calluses, 251–2
calorimetry, 184
Candida albicans, 282, 288
capable learner stage, 330
Carboflex, 407, 408
carbohydrates, 20
carbon fibres, 18, 436
Carbonet, 407, 408
care resistance *see* wash resistance
category scales, 388
cellular immune reaction, 268
cellulose, 9
CEN TC 248, 367
Central Institute for Labour Protection, National Research Institute (CIOP-PIB), 542
Centre for Biologics Evaluation and Research, 148–9
cephalosporin C, 301
chemical debridement, 41
chemical ionisation, 395
chemical vapour deposition, 349–50
chitin, 11–12
chitosan, 12–13, 337–8
chlorine bleach, 370–2
chromium, 270
chronic venous insufficiency, 482–3
chronic wounds, 40
clavi, 252
Clean Air Suit, 463, 464
Cleveland Clinic, 98
Clostridium difficile, 303–4, 305
clothing, 201
co-spinning, 182
coating, 176–7, 348–50
coating process, 158
cobalt, 270
cold stress, 201
  future trends, 437–40
    heat and pressure reduction combination to prevent bedsores, 437–8
    increased use of textile-based systems (reusable vs disposable), 437
    'open' systems avoidance: linting in the operation room, 438–9
    outlook on thermal systems for physiotherapeutic applications, 439–40
    spacer fabric cross section, 438
    textile-based bandage for electrical heating purposes, 440
    use of phase change materials, 439
    X-ray permeable systems using carbon fibres and other types of fibres, 438
  key issues and importance of preventing cold stress, 434–5
  textiles for patient heat preservation during operations, 434–40
    applications in maintaining patient temperature, 435–7
    main types to maintain patient temperature, 435, 436
cold sweat, 449
COLIPA guidelines, 162–3
collagen, 13
Commission Directive 2004/96/EC, 269
community-associated MRSA, 312
complexation with cyclodextrins, 156
composite finishing, 154
composite flow moulding, 148
compression bandages, 260–1
compression force, 489–90
compression pressure, 484–5
compression stockings, 260–1, 497
compression therapy, 54–9, 482–8
  application and parameters, 484
  applications and textile materials, 484–8
    compression pressure, 484–5
    effect of therapy to the human organism, 487–8
    pressure flow on the human leg according to Laplace, 485
    static pressure vs operating pressure, 485–6
    therapeutic pressure process, 486–7
  medical background: venous and lymphatic diseases, 482–4
    lymphoedema, 483–4
    varicose veins and chronic venous insufficiency, 482–3
conductive heat loss, 206
constant pressure liquid displacement method, 427
consumer perception tests, 328
consumer testing, 328
contact allergy, 268
Contreet Foam, 403–4
controlled release strategies, 173–4
convective heat loss, 206
copper wires, 436
corneocyte, 249
Corneometer, 168
corns *see* clavi
cosmetic Good Manufacturing Practices (cGMP), 158
cosmetic microcapsules, 158
cosmetic textile agents, 340

© Woodhead Publishing Limited, 2011

cosmetic textiles, 153–71, 339–40, 346
  application and release technologies, 154–60
  functionalities, cosmetotextiles and performance testing, 160–9
  future trends, 170–1
  safety evaluation and regulation, 169–70
cotton, 262
cotton-core nonwovens, 115
coverstock, 123
CTX-M enzymes, 311
cup method, 212–13
Cusick drape tester, 233
Cutometer SEM 575 Skin Elasticity Meter, 254
cyclodextrins, 182, 338, 351, 407
cytotoxic reaction, 268

Dacron, 137
Dacron prosthesis, 137
decubitus ulcer, 253–4
deep tissue injury, 253
degradable fibres, 67
Derma Smart, 29
dermacidin, 283
Dermatop, 168
determined explorer stage, 330
DEXON mesh, 135
diaper dermatitis, 321
diary studies, 328
dibutyrylchitin, 12
differential scanning calorimetric analysis, 183
digital image speckle correlation, 256
DIN 61 621, 367
DIN 1946–4 (1986), 445
DIN 54231:2005-11, 276
DIN 1946-2 (1994), 445
DIN EN ISO 3759, 464
DIN EN ISO 22612, 463
DIN EN ISO 9073-3, 463
DIN EN ISO 9073-10, 463
DIN EN ISO 11737-1, 463
DIN EN ISO 12945-2, 464, 470
DIN EN ISO 12947-1, 464, 470
DIN EN ISO 13938-1, 463, 470
DIN EN ISO 15797-2, 463
direct in vivo methods, 499
Directive 94/27/EC, 269
discrimination tests, 388
disposable surgical textiles, 444
Domagk, G., 299–300
Doppler ultrasonography, 53–4
drug delivery systems, 555–7
drug-releasing textiles, 173–91
  applications, 184–9
    antibacterial effects of wool fabrics, 186
    miscellaneous drug delivery applications, 189
    regenerative engineering, 188
    topical/transdermal drug delivery, 186–8
    wound care, 185
  classification, 175–6
    drug-releasing electrospun nonwoven fabrics, 176
    drug-releasing nonwoven fabrics, 176
    drug-releasing woven fabrics, 175
  fabrication and characterisation, 176–84
    bioconjugation, 180–2
    coating, 176–7
    drug-loaded textiles characterisation, 183–4
    electrospinning process, 180
    encapsulation, 177–80
    inclusion complexes, 182
    ion complexes, 182–3
    microfluidic device for microfibres extrusion, 178
    plasma/wet chemical treatment, surface grafts copolymerisation and co-spinning processes, 181
    process of drug loaded fibre production using wet spinning method, 179
  future trends, 190–1
Dry Web, 110
drying process, 96
Durepair, 140
dyes, 270
DynaMesh, 134
DynaMesh pp-light, 135
dynamic friction, 259
dynamic permeation cell, 213

E-vita, 139
EC No 1223/2009, 169
ECM *see* extracellular matrix
Ehrlich, P., 300
elastic cotton-core nonwovens, 115
electrically conductive textiles, 22
electronic noses, 394–5
electrospinning, 26, 179–80, 341, 548–9
  electrospun nonwoven SEM image, 549
  process, 180
  set-up, 548
electrospraying, 179
electrospun technology, 209
electrostatic flocking technology, 7
electrotherapeutic bandages, 22
elephantiasis, 484
'Elixir Sulphanilamide,' 300
elongation, 490
EN13795, 463, 475, 477
EN15797, 471
EN 13795, 116, 438
EN 13795-1 (2003), 444, 458
EN 13795-2 (2005), 444
EN 13795-3 (2006), 444
EN ISO 13938, 464
encapsulation, 177–80
endocrine disrupters (EDs), 84
energy conservation equation, 199
enteric coating method, 174
Environmental Health Perspectives, 85
epicutane test, 275, 276

© Woodhead Publishing Limited, 2011

ergonomic comfort, 447
ergonomic tests, 534–42
  clothing sets for studies, 536, 538
  clothing sets variants for studies in the microclimatic chamber, 538
  studies of underwear and vests made from superabsorbent nonwovens, 534–6, 537
    nonwoven containing Oasis fibres and cotton knitted fabric, 535
    sweat sorption dynamics of Oasis fibres and of the cotton knitted fabric, 537
    waistcoat construction, 535
    water vapour sorption of Oasis fibres and cotton knitted fabric, 536
  test conditions and testing procedure, 538–9
  water vapour sorption for cotton knitted fabric (ba) and nonwoven absorbing sweat, 538
Eschler Textile, 467
European Centre for Disease Prevention and Control, 125
European Committee for Standardisation, 381
European Cosmetics Directive (76/768/EEC), 161, 163
European Directive 93/42, 443
European Medicines Agency, 148
European Operating Room Nurses Association, 125
European standard DIN EN 14065, 380
European Standard EN 14065 RABC, 381
European Textile Service Association, 470
evaporative heat flow, 199
evaporative heat loss, 206
evidenced based medicine, 498
exhaust process, 158
expanded polytetrafluoroethylene, 134
extended spectrum beta-lactamases, 311
extracellular matrix, 551

F2451-05, 150
fabric air permeability, 109
fabric flexibility, 109
fabric hand, 223
fabric softener, 263
feminine hygiene, 320–1
feminine hygiene products, 318–19
fibre, 107–8
fibre bioreactors, 423–5
fibre bonding, 108
fibre finish, 109
fibre length, 229
fibre number, 228
fibre stiffness, 229
fibres *see* superabsorbent fibre
fibroin, 9
filtration coefficient, 426
finite element (FE) model, 65
Flair, 139
Fleming, A., 300
focus group discussions, 328
food allergy, 268
force–elongation behaviour, 488
formaldehyde, 269
friction coefficient, 255–7

gel permeation chromatography, 184
gelatin, 13–14
Global Organic Textile Standard, 275
GORE VIABAHN, 139
GORETEX, 136
government regulations, 101
graft copolymerisation, 181
granular layer, 248
Gravimetric Absorbency Testing System, 213

healthcare
  modern textiles and biomaterials, 3–29
    chitosan membranes morphology, 13
    contacting behaviour and transmission phenomenon, 14–16
    fibres classification used in medical textiles, 6
    filter efficiency, 17
    future trends, 22–9
    information sources and advice, 29
    manufacturing/processing technologies and fibre diameter, 6
    medical textiles products properties, 9–14
    research examples and product development, 18–22
    role, 4–5
    stability and compactness engineering, medical textile systems, 16–18
    textile structures and technique used, 7
    types and medical applications, 5–9
healthcare-associated infections, 303–6
healthcare costs, 97–100
  cost analysis breakdown, 98–9
  hidden environmental product cost resulting to waste, 99–100
  reusable and disposable surgical gowns cost comparison, 99
  strategies, 97–8
  total health expenditures, gross domestic product (GPD), 97
  waste and hidden cost, 99–100
  world healthcare costs, 97–8
heat preservation
  use of textiles during patient operation, 434–41
    applications in maintaining patient temperature, 435–7
    future trends, 437–40
    key issues, 434–5
    main types of textiles used, 435
heat storage rate, 199
heat stress, 201
hemodialyzer, 423

© Woodhead Publishing Limited, 2011

hi-tech textiles
interactive wound therapies, 38–75
venous leg ulcers and management, 52–67
wound dressing structures, 67–74
wound dressings, 43–52
wounds, 39–42
high absorbency, 109
high performance liquid chromatography, 184
hospital laundries
bleaching and optical brightening, 370–3
alkylbenzenesulfonate, 371
chlorine bleach, 370–2
hydrogen peroxide and addition compounds, 372–3
linear alkylbenzenesulfonate and highly branched alkylbenzenesulfonate, 372
optical brighteners, 373
peracetic acid, 373
impact on hygiene of medical textiles, 369–78
surfactants, 369–70
washing processes, 373–8
key issues, 361–9
laundry disinfection, 365–7
washing, drying machines, centrifugal machines and washing extractors, 361–5
role in medical textiles, 360–86
future trends, 382
state of the art, 381–2
testing and quality control of hygienic properties, 378–81
European Standard EN 14065 RABC, 381
logo RAL-quality mark 992 'Appropriate Laundry Care,' 379
RAL quality mark 992, 378–80
RAL quality mark for commercial laundries, 380–1
textiles for hospitals, 367–9
washing, drying machines, centrifugal machines and washing extractors, 361–5
continuous batch washers in counter-flow with individual machines, 362
continuous flow washers or automated inline washers, 362–5
counter-flow washers, automated inline washers and continuous batch washers, 361
laundry moving in interior drums, 364
washing in counter-flow, 362
washing processes, 373–8
basic findings during the initial years, 373–4
from 1925 to 1950, 375–7
from 1950 to 1970, 377
from 1970 to present, 377–8
human cell, tissue and cellular and tissue-based products (HCT/P), 149
human trial method, 213–14
hyaluronan, 14
hyaluronic acid *see* hyaluronan
hydraulic permeability, 426
hydrocolloid dressings, 407–8
hydrogel dressings, 523–4
hydrogen peroxide, 372–3
hydrophilic finish, 235
hydrophilic treatment, 466
Hydrosheath, 146
2-hydroxyethyl methacrylate, 518
hygroscopicity, 527–9
hyperkeratotic changes, 251–2
hyperpigmentation, 251
Hytrel, 210

IgakiTamai, 140
immediate-type allergy, 268
immune complex formation, 268
immuno-fluorescence method, 54
incontinence products, 237–8
indentation test, 255
infection
future challenges, 310–12
Acinetobacter baumannii, 310–11
community-associated MRSA, 312
extended spectrum beta-lactamases, 311
prevention and control of infection and the role of medical textiles, 297–313
antibiotic resistance mechanisms, 302–3
antibiotics, 299–301
historical examples of serious infections, 298–9
holistic approach to preventing infections, 312–13
principles and practice of prevention and control in hospitals, 306–9
breaking the chain of infection, 308–9
chain of infection for *C. difficile*, 308
host factors, 307–8
routes of transmission, 307
sources of infection, 307
role of textiles in prevention and control, 309–10
anti-adhesive wound dressings, 309–10
antimicrobial wound dressings, 309
superbugs and healthcare-associated infections, 303–6
number of *C. difficile* infections and deaths in England, 306
number of MRSA bacteraemia cases and deaths in England, 305
scale of HAI problem, 305–6
inhalation allergy, 267
insecticide allergy, 268
interactive wound therapies
hi-tech textiles, 38–75
venous leg ulcers and management, 52–67
wound dressing structures, 67–74
wound dressings, 43–52
wounds, 39–42
Intergard Silver, 139
Intermountain Healthcare System, 99

© Woodhead Publishing Limited, 2011

International Union of Societies for Biomaterials Science and Engineering, 150
interpenetrating network, 350–1
intrinsic resistance, 302–3
ion complexes, 182–3
IPN *see* interpenetrating network
irritant contact dermatitis, 250
ISO 7198, 150
ISO 7730, 198
ISO 9886, 214
ISO 10551, 214
ISO 11092, 213
ISO 13485, 141
ISO 10 993, 149
ISO 14 155, 150
ISO 22 442, 150
ISO 25 539, 150
ISO 5085-1, 212
ISO 5085-2, 212
ISO 10993-4: 2002, 344
ISO 10993-5:1999, 344
ISO 10993-10: 2002, 344
ISO 11092 (1993), 447, 448, 452, 458
ISO 14184-1:1998, 276
ISO 20743-Method 10.1, 396
itraconazole, 186

Japanese Law 112, 271
'jeans button allergy,' 269, 275
JIS L 1902, 343, 344
'jumping genes,' 303

kaltostat, 46
kapock fibres, 263
Kawabata evaluation system, 223
keratin, 9
Kikuhime device, 67

Laplace's law, 56
latex allergy, 270
laundering, 95–6
layer-by-layer assembly, 349
leggings allergy, 270
lichen amyloidosis, 259
Life Cycle Assessment, 81–2, 331–3
line scales, 388
lipase, 341
lipoedema, 484
liquid filtration systems, 16
liquid interaction properties, 109
Lithothamnium calcareum, 286
long-stretch bandages, 490
Lycra, 278
lymphoedema, 483–4
Lyocell, 46, 262–3
  fibres, 284–6
  process, 285
Lyofoam C, 407
Lyoplant, 140
Lysorb, 512

macular amyloidosis, 259
maggot debridement therapy, 42
magnitude estimation, 389
Malassezia spp., 282
mass spectroscopy, 184
mecA gene, 304
mechanical debridement, 41
mechanical skin contact, 222–3
mechanical skin irritations, 248–63
  factors causing textile to be mechanically irritating, 258–63, plate IV, plates II & III
    bedding, 261–2
    Black heel. Intracorneal bleeding due to share forces by socks and shoes, Colour Plate III
    compression stockings and bandages, 260–1
    Keratosis follicularis in an atopic person, Colour Plate I
    Plantar callus, Colour Plate II
    socks, 260
    textile roughness on atopic skin, Colour Plate V
    textiles for atopic and sensitive skin, 262–3
    towels, 259–60
  human skin, 248–50
  measurement of irritating mechanical factors, 254–8
  skin irritation, 250
  skin responses to mechanical forces, 251–4
    black heel, 252–3
    blisters, 251
    classification of pressure sores, 254
    decubitus ulcer, 253–4
    hyperkeratotic changes, 251–2
    hyperpigmentation, 251
medical bandages
  and stockings with enhanced patient acceptance, 481–501
  applications and compression textiles, 482
  classification
    adhesive properties, 492
    application period, 492
    elongation properties, 491
  compression properties, 497–500
  compression textiles: properties and applications, 489–93
    essential product properties, 490
    spacer fabrics for compression bandages, 491
  compression therapy, 482–8
    application and parameters, 484
    applications and textile materials for compression therapy, 484–8
    medical background: venous and lymphatic diseases, 482–4
  improving patient acceptance, 493–500
    clothing physiological properties test results, 495

© Woodhead Publishing Limited, 2011

essential product properties, 493–4
future trends and possibilities in textile finishing, 494–6
improvement of thermo-physiological properties, 494
key issues and role, 482–93
textile compression materials: classification of means of compression, 488–93
compression classes for compression stocking, 493
textile properties as basis for compression materials, 488–9
compression textiles force-elongation behaviour, 489
elastic vs inelastic textiles in force-elongation behaviour, 489
medical drapes, 277
medical filters
evaluation and characterisation, 425–30
contact angle of a liquid on a horizontal surface, 428
measurement of diffusion/hydraulic permeability, 425–6
pore size and pore size distribution measurement, 426–8
surface properties evaluation, 428–30
hollow fibre bioreactors application, 423–5
hollow fibre woven fabrics for an artificial lung, 424
key issues, 419–22
hollow fibre dialyzer, 421
textiles, 419–30
future trends, 430
medical textiles
and biomaterials, healthcare, 3–29
and biomaterials for healthcare
contacting behaviour and transmission phenomenon, 14–16
information sources and advice, 29
medical textile products properties, 9–14
research examples and product development, 18–22
role, 4–5
stability and compactness engineering, medical textile systems, 16–18
types and medical applications, 5–9
contact sensations on the skin, 221–43
applications, 236–41
applications in skin contact, 222
distinguishing from fabric hand, 223
future trends, 241
importance of mechanical skin contact, 222–3
skin contact sensations, 223–7
textile properties influencing skin contact sensations, 227–36
future trends, 22–9
scientific strategies, nanosystems and smart products, 26–9
tissue engineering concepts, 24–6
trends and challenges of new products and applications, 22–3
infection prevention and control, 297–313
antibiotic resistance mechanisms, 302–3
antibiotics, 299–301
future challenges, 310–12
historical examples of serious infections, 298–9
holistic approach to preventing infections, 312–13
principles and practice of infection prevention and control in hospitals, 306–9
role of textiles, 309–10
superbugs and healthcare-associated infections, 303–6
odour control, 387–410
future trends, 410
key issues in medical applications, 396–400
odour measurement, 388–96
textiles, 401–10
research examples and product development, 18–22
modern textile architectures and specialised materials, 21–2
visible fibre to molecular shape modifications, 18–21
role of hospital laundries, 360–86
additional information, 383–6
future trends, 382
impact on hygiene of medical textiles, 369–78
key issues, 361–9
state of the art, 381–2
testing and quality control of hygienic properties, 378–81
thermal comfort, 198–215
fundamentals, 198–201
future trends, 214–15
healthcare workers and patients in hospital environment, 201–5
surgical gowns, 205–11
thermal properties evaluation and testing, 212–14
medical waste incinerators, 83–4
'Medically Tested/Tested for Toxins label,' 274
Mefoxin, 185
Meloxicam, 187
Memorandum of Understanding, 82
mepitel, 46–7
2-mercaptobenzothiazole, 277
Mercy Healthcare, 98
Mersilene, 134
metabolic heat, 199
2-methacryloyloxyethyl phosphorylcholine, 420–1
methicillin-resistant *Staphylococcus aureus*, 303–4

© Woodhead Publishing Limited, 2011

methicillin-sensitive *Staphylococcus aureus*, 304
microencapsulation, 23, 155–6
micropackaging, 154
microporous polymer coating, 210
Minnesota Technical Assistance Program, 82
momcilovic, 14
monolithic coating, 210
mosquito repellent garments, 344–5

N-halamine compounds, 339
N-methylmorpholine-*N*-oxide monohydrate, 284
nanofibres, 547
nanofibrous textiles
  applications, 551–9
    drug delivery systems, 555–7
    tissue engineering, 557–9
  electrospinning, 548–9
    electrospun nonwoven SEM image, 549
    set-up, 548
  future trends, 559–60
  medical applications, 547–60
  nanofibres, 547
  nanofibrous structures properties, 550–1
  production process, 548–50
    other techniques, 550
  wound dressings, 551–5
    handheld device for electrospinning, 555
    wound area at different healing times of wounds, 553
nanosystems, 26–8
nanotechnology, 309
natural fibres, 408–9
'Naturtextil IVN zertifiziert BEST,' 275
needle punch fabrics, 118–19
neoprene, 239
Neosalvarsan, 299
NeuraGen, 146
Neuro-Patch, 140
Neurolac, 146
NeuroTube, 146
newborn stage, 330
Newcell, 284
NFPA code 99, 88
nickel, 269
non-degradable fibres, 67
nonwoven fabric, 208
nonwoven materials
  issues, 107–111
    fibre, 107–8
    fibre bonding, 108
    fibre finish, 109
    performance requirements, 109–11
    web assemblage, 108
    web finishing, 108–9
  medical applications, 117–25
    bed linens, 122
    clothing, 123
    cloths and wipes, 123–4
    drapes and cover cloths, 122
    feminine sanitary napkins, 124
    incontinence products, 123
    medical gauze, 119
    nonwoven application in healthcare/hygiene sector, 121
    nonwoven application in non-implantable medical textiles, 118
    surgical caps, 122
    surgical gowns, 120–1
    surgical masks, 122
    tampons, 124
    tissue engineering, 125
    underpads, 124
    wadding, 120
    wound care products, 118–19
  strengths and limitations, 116–17
    limitations, 117
    strengths, 116–17
  technologies for medical applications, 106–26
    future trends, 125–6
    information sources and advice, 126
    nonwoven issues, 107–111
    strengths and limitations, 116–17
    types, 111–16
nonwoven technologies
  materials, medical applications, 106–26
    future trends, 125–6
    nonwoven issues, 107–111
    strengths and limitations, 116–17
    types, 111–16
  types, 111–16
    airlaid nonwovens, 113–14
    chemical-bonded nonwovens, 115–16
    composites, 114–15
    spunbound (SB) and meltblown (MB) nonwovens, 112–13
    spunlaced nonwovens, 111–12
    spunlaid nonwovens, 112
    thermal bonded nonwovens, 114
nonwoven vari-stretch compression bandage, 63
NPB5, 61
nurses' occupational clothing, 236–7

Oasis fibres
  changes in Oasis 102 fibre moisture over time, 515
  free absorption of salt water, 516
  properties, 515–16
  tenacity and strength, 514
  type 102 fibre moisture content, 515
  type 102 fibres properties, 514
  water vapour absorption capacity, 513
occupational clothing
  2× and 75× processes according EN 15797
    bursting strength values comparison, 472
    pilling values comparison, 473
    sweat transportation values comparison, 474
    wetting index values comparison, 475
  cleanliness, 464

© Woodhead Publishing Limited, 2011

fabric surface visualisation after 2× and 75× cycles
material 1, 473
material 2, 474
future trends, 477–9
cost-savings in the medical sector, 477
integrated consideration in the operating theatre and hospital, 477–8
multifunctional textiles, 478
sustainability, 478–9
improving comfort in nurses' occupational clothing, 464–8
possible changes description in textile construction to improve comfort, 466
research project ProInno, 467–8
improving durability of nurses' clothing in industrial laundering processes, 468–75
Hohenstein Quality standard 704, 469
measurement and guideline values of capability for industrial washing, 469–70
possible changes description in textiles to improve efficiency, 470–1
procedure general description with reusable textiles, 468–9
research project ProInno, 471–5
test results of optimised materials relating mechanical properties, 471
knitted microfibre fabrics applications, 476–7
clothing for the operating theatre, 477
nurses' occupational clothing, 476
materials and methods, 463–4
materials description, 463
test methods description, 463–4
resource saving, washing, drying, durability and nosocomial infections, 475–6
textile materials for nurses, 461–79
wearer comfort, 464–5, 467
defining, 464–5
definition, 464–5
guideline values in workwear, 465
measurement, 465
optimised textiles in comparison to a standard product, 467
optimised textiles vs standard product, 467
Occupational Exposure to Bloodborne Pathogens Rule, 84
Occupational Health and Safety Administration, 84
odour-absorbing textiles, 405–9
activated charcoal, 405–7
examples, 406
natural fibres, 408–9
other absorbent materials/polymers, 407–8
odour control
antimicrobial textiles, 401–5
wounds treated with Contreet Foam, 404
instrumental evaluation, 393–5
approaches to measuring odorants on textiles, 393–4
chemical ionisation in real-time analysis, 395
electronic noses, 394–5
key issues in medical applications, 396–400
textiles, 400
medical textiles, 387–410
future trends, 410
microorganisms, 398–400
average number of bacteria and foot odour, 399
odour-absorbing textiles, 405–9
activated charcoal, 405–7
activated charcoal based wound dressings, 406
natural fibres, 408–9
other absorbent materials/polymers, 407–8
odour measurement, 388–96
antimicrobial efficacy tests, 395–6
sensory assessment, 388–93
bacterially generated sweat-odour profiles, 392
odour assessment scoring tool, 390
qualitative description of wound and body odours, 391–3
sensory test methods, 388–9
wound and body odours, 389–91
sources, 396–8
textiles, 401–10
refurbishment, 409–10
scented textiles, 409
Oeko-Tex 1000, 158
Oeko-Tex Standard 100, 155, 158, 270, 271–4
operating pressure, 486
operating room-protective clothing, 237
optical brighteners, 373
Optilene Mesh Elastic, 135

padding process, 157
Panton–Valentine leucocidin, 312
Parietex ProGrip mesh, 135
passive warming systems, 436
Pasteur, L., 307
patch test, 275, 276
PCL *see* polycaprolactone
penicillin, 300–1
peracetic acid, 373
PERSIL, 374
personal health care and hygiene
absorbent products, 316–33
application example, 329–30
future trends, 330–3
key issues, 319–25
product testing, 325–9
product types, 316–19
personal protective equipment, 84, 86
PGA *see* polyglycolic acid
pharmaceutical allergy, 268
phase change materials, 240, 439
Phi-X 174 Bacteriophage Penetration test, 89
phlebo-lymphoedema, 484

© Woodhead Publishing Limited, 2011

phlebography, 54
photoplethysmography, 54
physiological comfort, 198, 447
physiological stress
  evaluation of surgeon occupational clothing, 443–59
    controlled wear tests, 451–6
    elements of comfort, 447
    historical background, 443
    influences on wear properties, 444–6
    purchasing criteria, 456–8
    recommendations, 458–9
    relevant parameters for comfortable textiles, 447–8
    surgical gowns, 444
    sweating, 448–51
PLA *see* polylactic acid
plague, 298
plasma/wet chemical treatment, 180–1
plasmids, 303
PN-EN 149+A1:2009 (2009), 543
PN-P-04635 (1980), 527
poly(2-hydroxyethyl methacrylate), 519
polyacrylonitrile, 28
polyamide, 5, 134
polyamide 6, 20
polycaprolactone, 552
polycondensation, 155–6
polydioxanone, 140
polyester, 5, 7
poly(ethylene-*co*-vinyl acetate), 185
poly(ethylene glycol), 422
polyethylene terephthalate, 5, 8, 134
Polyflex, 140
polyglactin 910, 140
polyglycolic acid, 10–11, 142, 552
polylactic acid, 5, 8, 10–11, 185, 552
  fibre mesh, 20–1
polylactid acid, 140
polypropylene, 5, 134
polytetrafluoroethylene, 5, 46
poly(vinyl alcohol), 187
polyvinylidene fluoride, 134
polyvinylpyrrolidone, 421–2
pressure sore *see* decubitus ulcer
primary lymphoedema, 483
primary pneumonic plague, 298
printing process, 158
prodrugs, 174
Prontosil Rubrum, 299–300
PROPATEN, 139
proton transfer reaction mass spectrometer, 395
pulse lavage *see* wound irrigation
pyrethrum, 339

quaternary ammonium compounds, 337
quick & dirty tests, 451

RABC *see* Risk Analysis and Biocontamination Control System
radiant heat loss, 206
RAL 992/1, 380
RAL 992/2, 380
RAL 992/3, 380
RAL-GZ 992/3, 380
RAL quality mark 992, 378–80
  commercial laundries, 380–1
    hospital laundry, 380
    household linen and contract textiles, 380
    laundry of the food processing industry, 380
    quality mark abroad, 380–1
  historical development, 378–80
RAL-RG 992/2 Krankenhauswäsche, 379
ranking, 388
regenerative medicine
  cartilage: closing three-dimensional defects, 144–6
    chondrocytes in PGA scaffold, 145
  information sources and advice, 150
  liver: metabolic active biohybrid organs, 146–7
  materials, structures, cells and mediators, 142–4
    biomaterial structures, 143
    cells, 144
    materials and structures, 142–4
    signalling molecules, 144
  nerves: guided tissue regeneration, 146
    tubular nerve guide with integrated fibres with microgrooves, 147
  others, 147–8
  regulatory aspects, 148–9
  testing of implants and materials, 149–50
  textile implants, 132–50
  trends, 149
Release, 407
resistance-encoding plasmids, 303
resorbable fibres, 67
reusable medical textiles, 80–102
  advantages, 81–6
    environmental advantages, 81–2
    physical properties and performance, 85–6
    public health advantages, 82–5
  future trends, 100–2
    antimicrobial technology, 101
    comfort studies, 100
    environmental marketing claims guide, 102
    Healthcare Laundry Accreditation Council (HLAC 2010), 101
    improve performance incontinence materials, 100–1
  healthcare costs, 97–100
    cost analysis breakdown, 99
    hidden environmental product cost resulting to waste, 100
    reusable and disposable surgical gowns cost comparison, 99
    strategies, 98–9
    total health expenditures, gross domestic product (GPD), 97

© Woodhead Publishing Limited, 2011

waste and hidden cost, 100
world healthcare costs, 97–8
historical perspective, 80–1
patient apparel, 91–2
characteristics and practices, 91–2
fabrics, 91
flammability requirements, 92
physical properties and performance, 85–6
processing procedures, 94–7
drying, 96
laundering, 95–6
sorting, 94–5
steam sterilisation, 96–7
public health advantages, 82–5
challenges, 83
children's risk, 84
elderly risk, 85
healthcare workers threat, 84
medical waste incinerators (MWIs), 83–4
opportunities, 83
US EPA medical waste incinerators final rule, 84
waste and human health connection, 83
waste implications and infectious disease in society, 85
sheets and pillowcases, 92–3
100% polyesters, 92
knit sheets, 92–3
types, 86–94
AAMI standards, fluid barrier performance, 90
patient apparel, 91–2
precaution apparel, 90–1
professional attire, 91
regulatory controls, 89–90
sheets and pillowcases, 92–3
surgical packs, 86–9
surgical toweling, 93
underpads, 93–4
underpads, 93–4
basic technology, 93–4
bed sore prevention, 94
cost, 94
reusable surgical textiles, 444
rewet, 327
rifampicin, 301
Risk Analysis and Biocontamination Control System, 381

SAFEC, 437
Salvarsan, 299
SAP *see* superabsorbent polymer
scanning electron microscopy, 183, 549
scented textiles, 409
Scientific Committee on Consumer Safety, 170
scrubs, 277
SeaCell textiles, 286–9
second skin, 248
selected ion flow tube mass spectrometer, 395
Semmelweis, I., 306–7
sensible perspiration, 235
sericin, 270
short-stretch bandages, 490–1
silk, 262
silver, 286–7, 339
Silver Graft, 139
silver sulfadiazine, 14
skin contact sensations, 223–7
clinging, 226
influence of moisture, 226
initial temperature sensation, 226–7
initial temperature sensation on pillows, 227
reddening of skin/erythema, 227
scratching, 225
sleekness/roughness, 225
softness, 224–5
stiffness, 225
skin irritation, 250
skin protection, 321–4
skin sensorial comfort, 222, 223
influencing textile properties, 227–36
apparatus for testing textile's hairiness, 230
fibre ends protruding from textile bulk, 228
hairiness, 227–31
image analysing process to obtain length and number of fibre ends, 231
measuring fabric's stiffness, 233
skin contact surface structure, 231–2
stiffness, 232–4
sweat management, 234–6
system for testing the sorption speed of a sweat drop by a textile, 236
medical textiles, 221–43
applications in skin contact, 222
distinguishing from fabric hand, 223
future trends, 241
importance of mechanical skin contact, 222–3
main results, 242–3
medical textiles applications, 236–41
bandages, 238–9
bed linen and coverings, 239–40
discomfort as function of hairiness, 239
impaired skin, 240–1
incontinence products, 237–8
nurses' occupational clothing, 236–7
operating room-protective clothing, 237
skin contact sensations, 223–7
clinging, 226
influence of moisture, 226
initial temperature sensation, 226–7
intitial temperature sensation on pillows, 227
reddening of skin/erythema, 227
scratching, 225
sleekness/roughness, 225
softness, 224–5
stiffness, 225
Skintex, 166–7, 168–9, 346

© Woodhead Publishing Limited, 2011

small base testing, 328
smart gowns, 210
smart products, 28–9
Smartcel Clima, 439
socks, 260
Soda–Soap Procedure, 375
SOFRADIM, 135
solute permeation method, 428
sonochemical method, 348
sorbsan, 46
Spandex, 278
speciality medical fibres, 67
spraying process, 158
spunbond–meltblown–spunbond (SMS) fabric, 209
spunlace nonwoven fabric, 111–12, 209
spunlacing, 111–12
spunlaid nonwovens, 112
staphylococcal cassette chromosome *(SCCmec)*, 304
Staphylococcus aureus, 281–2, 286, 288
static friction, 259
static pressure, 486
Staverman reflection coefficient, 426
steam sterilisation, 96
  typical conditions, 96
stockings
  enhanced patient acceptance, 481–501
    improving patient acceptance, 493–500
    key issues and role, 482–93
stockings colour allergy, 270
stratum corneum, 248–9
stratum corneum chamotryptic enzyme, 283
streptomycin, 301
sulfanilamide, 300
sulfonamides, 299
superabsorbent fibre, 16, 110
  application in half masks, 542–3
    filtering half-mask, 543
  applications for comfort improvement, 525–34
    description of work conditions, 525
    new textiles types with superabsorbent fibres, 525–6
    variants of nonwovens, 526
  applications in hygiene products and medical textiles, 520–5
    covers for operating room tables, 524
    hydrogel dressings, 523–4
  applications in medicine, 518–20
    contact lenses, 519
    hybrid organs, 520
    hydrogels in tissue engineering, 519
    reconstruction of blood vessels and human muscle cells, 520
    systems for the administration of drugs, 519
  average changes
    relative humidity and temperature under clothing – back – during tests, 541
    relative humidity under clothing – chest – during tests, 540
    temperature under clothing – back – during tests, 541
    temperature under clothing – chest – during tests, 540
  ergonomic tests, 534–42
    clothing sets for studies, 536, 538
    clothing sets variants for studies in the microclimatic chamber, 538
    studies of underwear and vests made from superabsorbent nonwovens, 534–6
    test conditions and testing procedure, 538–9
    waistcoat construction, 535
    water vapour soprtion for cotton knitted fabric (ba) and nonwoven absorbing sweat, 538
  forms and their properties, 510–16
    fibre form, 512–16
    granulate and powder form, 511–12
    specification used for hygiene products, 512
    superabsorptive fibres in the world, 512
  materials development stages according to appropriate patents, 516–18
    polyurethane superabsorbent fibres characteristics, 517
  medical applications, 505–44
  methods of obtaining superabsorbent polymers and their chemical structure, 506–10
  nonwovens
    dynamics of sweat sorption for the nonwoven, 537
    effectiveness of sweat sorption, 532
    effectiveness of sweat sorption for basic nonwovens, 532
    hygroscopicity, 527
    Oasis fibres and cotton knitted fabric, 535
    thermal resistance of basic nonwovens, 527
    water vapour absorption over time by needle punched nonwoven A, 528
    water vapour absorption over time by needle punched nonwoven G, 529
    water vapour sorption of Oasis fibres and cotton knitted fabric, 536
  Oasis fibres
    changes in Oasis 102 fibre moisture over time, 515
    free absorption of salt water, 516
    properties, 515–16
    tenacity and strength, 514
    type 102 fibre moisture content, 515
    type 102 fibres properties, 514
    water vapour absorption capacity, 513
  properties, 513
  SAPs application for the hygiene products, 520–3
    adult incontinence products, 522–3
    baby diapers, 521–2

© Woodhead Publishing Limited, 2011

textiles assessment with superabsorbent fibres, 526–34
hygroscopicity, 527–9
results of measurements on materials, 526–7
sweat sorption dynamics, 529–34
superabsorbent polymer, 110, 505
superbugs, 303–6
support stockings, 277–8
surfactants, 369–70
surgical gowns
choosing textiles for OR use, 443–59
historical background, 443
controlled wear tests, 451–6
calculated range of utility', gown no. according AIF-report 11090, 453
calculated range of utility' according the Hohenstein Test Report (2000), 455
classification of barrier textiles, 453
physiological profile of demand for OR barrier and backside textiles, 452
relative humidities in a microclimate, 454
wear tests with reusable and disposable gowns, 452–6
elements of comfort, 447
evaluation of parameters relevant for comfortable textiles, 447–8
influences on wear properties, 444–6
clothing system, 446
environmental climate, 445
standard person workload during different activities, 446
wearer personal condition, 446
workload, 446
materials used for the two performance classes, 444, 445
critical area, 445
medical product according to Standard EN 13795, 444
purchasing criteria, 456–8
comfortable surgical gowns, 456–7
disposable and reusable surgical gowns, 457–8
polarity of criteria to assess the surgical textiles performance, 457
sweating as an effect of physiological stress, 448–51
thermal mannequin, 449
Surgical Materials Testing Laboratory, 42
surgical packs, 86–9
coated and laminated fabrics, 88–9
coated fabrics, 89
polytetrafluoroethylene (PTFE) microporous membranes, 89
seam sealing, 89
fluid resistant, continuous filament polyester, 87
fluid resistant, polyester/cotton materials, 87
fluoropolymer reapplication methods, 88
sheeting materials, 87
static control polyester materials, 88
suspension test, 343
sweating guarded hot plate method, 213
swelling, 510
systemic antibiotics, 42

'tansposons,' 303
Tencel, 284
tensile properties, 109
tension elasticity, 488
tension free repair, 134
tension-free transvaginal tape, 135–6
Tewameter, 168
textile finishing, 241
textile friction analyser, 261
textile implants
advantages, application fields, materials, 133–4
implantable textile medical devices major applications, 133
hernia meshes, 134–6
trends, 135–6
typical warp knitted structure, 135
information sources and advice, 150
others, 140
resorbable stents for biliary and enteral applications, 141
regenerative medicine, 132–150
regulatory aspects, 141
testing of implants and materials, 149–50
vascular prosthesis, 136–40
history, 137
other blood-contacting devices, 140
production process, 137–8
trends, 139
warp knitted PET bifurcation vascular prosthesis, 138
textile materials
occupational clothing for nurses, 461–79
cleanliness, 464
future trends, 477–9
improving comfort in nurses' occupational clothing, 464–8
improving durability of nurses' clothing in industrial laundering processes, 468–75
knitted microfibre fabrics applications, 476–7
materials and methods, 463–4
resource saving, washing and drying, durability and nosocomial infections, 475–6
textiles
application and release technologies, 154–60
binding technologies, 156–7
cosmetic finish application via padding and exhaust, 157
entrapment technologies, 154–6
exemplary application and release technologies comparison, 155
finishing/application technologies, 157–8

© Woodhead Publishing Limited, 2011

microcapsules, 156
quality control, 158–60
applications in maintaining patient temperature, 435–7
cosmetic effects, 153–71
application and release technologies, 154–60
functionalities, cosmetotextiles and performance testing, 160–9
future trends, 170–1
safety evaluation and regulation, 169–70
functionalities, cosmetotextiles and performance testing, 160–9
claim substantiation, 162–4
cosmetics: definitions and functionalities, 161–2
cosmetotextile, 162
performance testing, 164–9
reloading application example, 163
skin, 161
main types to maintain patient temperature during operations, 435, 436
spacer fabrics thermal resistance vs standard- and foam-constructions, 436
medical filters, 419–30
evaluation and characterisation, 425–30
future trends, 430
hollow fibre bioreactors application, 423–5
key issues, 419–22
occupational clothing evaluation for OR use, 443–59
controlled wear tests, 451–6
elements of comfort, 447
evaluation of parameters relevant for comfortable textiles, 447–8
historical background, 443
influences on wear properties, 444–6
purchasing criteria, 456–8
surgical gowns, 444
sweating as an effect of physiological stress, 448–51
patient heat preservation during operations, 434–40
future trends, 437–40
key issues and importance of preventing cold stress, 434–5
performance testing, 164–9
cosmetic product transfer from cosmetotextile to skin, 165
efficacy testing via objective measurements, 166–8
efficacy testing via subjective measurements, 168–9
skin transfer studies, 164–6
wash and wear efficacy test, assessing skin hydration, 167
wash and wear test, 166
quality control, 158–60
initial loading, 158–9
wash permanency curve, 160
wash resistance, 159–60
The Hohenstein Institute, 465, 467, 469
therapeutic pressure process, 486–7
recommended values for therapeutically normal pressure gradients on the leg, 486
thermal comfort, 198–215
fundamentals, 198–201
future trends, 214–15
healthcare workers and patients in hospital environment, 201–5
healthcare workers and patients, 204–5
hospital environment, 202–3
temperature setting in the operating room, 203–4
surgical gowns, 205–11
textile materials used for medical textiles and factors, 207–10
fabrics used in surgical gowns and thermal comfort, 208–9
fibres/yarns/fabrics and their relationship with thermal comfort, 207–8
new technology used in surgical gowns and thermal comfort, 209–10
thermal properties evaluation and testing for medical textiles, 212–14
fundamental textile properties, 212–13
human trial, 213–14
thermal manikins, 213
thermal manikins, 213
thermal resistance, 206
thermogravimetric analysis, 183
thermoplastic semi-IPN, 351
thiurames, 277
thromboembolic stockings, 277–8
TiMesh, 136
tissue engineering, 142, 557–9
concepts, 24–6
Tissue Engineering and Regenerative Medicine International Society, 150
TITV Greiz, 435, 440, 494
towels, 259–60
‘Toxproof,’ 275
transepidermal water loss, 249
tricalcium phosphate, 28
Trox, 187–8

ultrafiltration, 423
ultrasonic irradiation, 348–9
ultrasound scanning, 54
University of Minnesota, 82
Unna’s boot, 56–7
U.S. Environmental Protection Administration, 82
U.S. Federal Trade Commission, 102
U.S. Food and Drug Administration, 89
US Patent 3670069, 516
US Patent 3940542, 516
US Patent 4721647, 517
US Patent 5002814, 517
US Patent 5304420, 518
US Patent 6783852 B2, 518

© Woodhead Publishing Limited, 2011

Valiant, 139
vancomycin, 304
VascuGraft, 136
venous leg ulcers, 52–67
  causes, 53
  compression therapy, 54–9
    bandage application, 58–9
    bandages illustration, 59
    compression and pressure relationship, 57
    compression bandages classification, 55
    compression system, 56–7
    elastic bandages classification, 55
    ideal compression bandages, 56
    ideal pressure, 57–8
  diagnosis, 53–4
    Doppler ultrasonography, 53–4
    photoplethysmography and air plethysmography, 54
    ultrasound scanning, 54
  problems and novel bandages, 59–64
    novel padding bandages, 62
    pressure distribution, commercial padding bandages, 60
    pressure distribution, novel padding bandages, 61
  three-dimensional compression bandages, 64–7
    pilot user study, 66–7
    pressure profile, novel and commercial bandages, 66
    single layer bandage development, 65–6
    spacer fabric structure, 65
Vilmed, 119
Vilmed adhesive tape, 119
Vilmed orthopaedic cast paddings, 119
viscose, 5
Vypro II, 135

Waksman, S., 301
warp knitted structures, 68
  illustration, 70
wash resistance, 159–60
washing machines, 361–5
water convective systems, 434
wearer comfort, 464–5
  definition, 464–5
  guideline values in workwear, 465
  measurement, 465
  optimised textiles vs standard product, 467
web assemblage, 108
web finishing, 108–9
weft knitted structures, 68
  illustration, 70
wet-laid fabric, 209
Wilhelm method, 429
wind chill effect, 212
Winter Haven Hospital, 98
wool, 262
wool prickle, 224, 227
World Health Organisation, 84, 125
wound care
  fabric structures usage, 68–70
    nonwoven structures, 68–70, 71
    warp and weft knitted structures, 68, 70
    woven structures, 68, 69
  fibres and yarns usage, 67–8
  products and bandages, specification, manufacture and properties, 71–4
    compression bandage, 73–4
    flight socks, 74
    non-adherent wound contact layer, 71
    retention bandage, 72
    secondary wound dressing, 72
    support bandage, 72–3
wound debridement, 41–2
  autolytic, 41
  chemical, 41
  mechanical, 41
  surgical, 42
wound dressings, 551–5
  handheld device for the electrospinning of wound dressings, 555
  wound area at different healing times of wounds, 553
wound irrigation, 41
wounds, 39–42
  classification, 40
  dressing structures, 67–74
    fabric structures, wound care usage, 68–70
    fibres and yarn, wound care usage, 67–8
    specifications, manufacture, and properties, wound care products and bandages, 71–4
  dressings, 43–52
    activated charcoal cloth (ACC), 49–51
    antimicrobial, 51–2
    commercial odour -absorbent dressing, 50
    concept, 45
    hi-tech, 45–7
    ideal wound dressing, 44–5
    non-adherent dressings, 47–8
    odour-absorbent dressing, 50
    odour absorption dressings, 48–51
    types and application, 43
  malodour, 48
    activated charcoal cloth (ACC) wound dressing, 49–51
    causes, 48–9
    treatment methods, 49
  management, 41–2
    wound debridement, 41–2

X-ray permeable systems, 438

Yersin, A., 298
Yersinia pestis, 298

Zenith, 139

© Woodhead Publishing Limited, 2011