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Indoor Air Quality in Healthcare Facilities

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Stefano Capolongo · Gaetano Settimo
Marco Gola
Editors

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Editors
Stefano Capolongo
Department of Architecture, Built Environment and Construction Engineering
Politecnico di Milano
Milan
Italy

Marco Gola
Department of Architecture, Built Environment and Construction Engineering
Politecnico di Milano
Milan
Italy

Gaetano Settimo
Department of Environment and Health
Istituto Superiore di Sanità
Rome
Italy

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Foreword: Improving the Hospital's Indoor Air Quality

Among hospitals-related health risks, environmental factors play a key-role; this accounting for different rooms' specific use, patients' vulnerability and risk of overcrowding. For these reasons, air quality control in hospitals—and in healthcare facilities—in general—deserves scientific attention. This collection of papers offers a multidisciplinary perspective on the topic, starting from presenting the general concepts of indoor air quality, chemical, biological and physical risk factors in living and working places, then describing the most effective preventive measures that can (and must!) be implemented in order to ensure users' safety and adverse events' reduction and including healthcare-associated infections (HAIs).

General Concepts of Indoor Air Quality

The indoor air quality is an issue of growing scientific interest both because the risks due to exposure to air pollution in indoor environments become more evident and—also stated by WHO—of improving public health and quality of life (Settimo and D'Alessandro 2014). The European Union and more specifically the European Environmental Agency (EEA) highlighted, in the reports "*Environment and Human Health*" and "*Environmental Signals 2013*", that indoor pollution levels are affected by air quality, materials, rooms' ventilation, type of furniture, equipment and products, occupants' habits (including passive smoking) and the overall building management (European Commission 2014). The introduction of measures for energy saving also had a great importance, sometimes able to negatively influence several parameters that affect the health and well-being of occupants (Santarsiero et al. 2014; Signorelli et al. 2016).

The Italian Ministry of Health, with the Regions and the Autonomous Provinces, by the agreement of the September 27, 2001, have defined confined indoor "spaces and workplaces as non-industrial environments, such as housing, public and private

offices, community facilities (hospitals, schools, barracks, hotels, banks, etc.), spaces for recreational and social activities (cinemas, cafés, restaurants, shops, sports facilities, etc.) and public and private transport (car, train, plane, ship, etc.)" (Italy 2001). In 2013, the European General Directorate for Environment in the report "*Cleaner Air for All*," stated that the indoor air quality requires a specific policy response to the EU's broader strategy on air quality. The same document suggested valid options that are very expensive, such as the improvement of construction and ventilation systems, as well as buildings' monitoring (European Commission 2014).

Currently, some European countries, such as France, Germany, The Netherlands, UK, Belgium, Finland, Austria, Portugal and Norway have already introduced regulations regarding indoor pollutants for environmental and hygienic assessments. In this context, the WHO activities are of great utility, realizing for the first time guidelines, at the European level, regarding indoor air quality with reference to nine specific atmospheric pollutants present in confined environments: benzene, formaldehyde, carbon monoxide, nitrogen dioxide, radon, trichlorethylene, tetrachlorethylene, naphthalene and aromatic polycyclic hydrocarbons (WHO 2010).

Also the work done by technical committees, such as the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN), is of particular relevance: they have undertaken developments of specific standardized methods with which to carry out the measurements in indoor environments. In particular, the norm "*EN ISO 16000: Air in confined environments*" is constituted by several specific parts; many of these have been adopted in Italian Organization for Standardization (UNI), and this is a further advancement than previously realized.

Even in Italy, the awareness on indoor issues has grown significantly, and in recent years, several technical committees and research groups have worked on this topic, but they still have not developed a framework law on indoor air quality, and therefore, the reference is the Legislative Decree No. 81/2008 regarding too general workplaces' safety (Settimo and D'Alessandro 2014). The scientific community has been concerned specifically with this issue since 1990, when the first National Commission for pollution of indoor environment was established. The National Study Group on Indoor pollution, sponsored by the *Istituto Superiore di Sanità* (National Institute of Health, ISS), is working to provide shared technical and scientific documents, with the aim to promote common strategies at the national level, waiting for the framework law.

Currently, there are numerous organizations that are trying to improve the knowledge on indoor air quality's issues and to set priorities or objectives to be achieved. However, all of them tend to draw results concerning generic confined environments and not specific ones, such as healthcare facilities, that ought to have priority because of the vulnerability of their users and their health conditions, and

because they are characterized by particular pollutants related to specific activities as disinfectants, cytotoxic, anesthetic gases, etc. (Capolongo et al. 2015).

The Air Quality in Hospitals

To get a good quality within healthcare facilities, in addition to satisfying acoustic, visual, psychological and social comfort, the thermal comfort should be ensured and, especially, the air quality and the absence of environmental risk factors that represent the first requirement for quality and safety. The indoor air quality is influenced by the presence of biological and chemical contaminants that do not occur naturally in outdoor air, which modify its composition altering the quality.

The requirements of the air quality in healthcare facilities vary by health function and often even from room to room in relation to its use. Some areas, such as operating rooms, intensive care units, and isolation rooms, require a high efficiency filtration for protecting patients, staff and visitors, while other areas require the elimination of substances gaseous contaminants, chemical ones and odors to provide a more safe and pleasant workplace.

Indoor air quality in healthcare facilities is a growing concern resulting from changes in medical activities, the obsolescence of the structures and the presence of vulnerable users. The design of these architectures and their organization must be set up in order to meet their primary role, i.e. the health of occupants.

In order to reach an adequate air quality, a primary aspect is the hospital localization that must be as far away from pollution sources, such as factories, traffic congestion, parking lots, and waste deposits. Two other important features are the adequate design of façades and ventilation systems (HVAC). Moreover, the control of airborne microorganisms is crucial in hospitals' indoor spaces because the air can represent an important vehicle of infections (Pasquarella et al. 2008, 2012). In hospitals, where the microclimate control is associated with a strong need for sterilization, it is necessary to introduce air conditioning systems which, if poorly designed, managed and maintained, can become a source of indoor air contamination by themselves. In fact, many studies on air quality in artificial air-conditioned buildings showed an increasing focus on those diseases well known as *Sick Hospital Syndrome* (Cabo Verde et al. 2015).

Many disorders, such as allergies and irritations, up to pathological forms and respiratory infections, can arise from the presence of contaminants in the air, such as the well-known Legionella pneumophila, within cooling towers and various sections of HVAC systems (Montagna et al. 2014). Among the components of the air system, for which specific performance levels relating to air quality must be verified, air ducts are crucial because they convey the replacement of air towards

the healing environments with levels of purity and quantity, such as to reach conditions of comfort.

Conclusions

Currently, ISS is carrying out various reports, according to WHO recommendations. Among the national scientific societies, the *Società Italiana di Igiene* (Italian Society of Hygiene, Preventive Medicine, and Public Health, S.It.I.), and especially the working groups GISIO (Italian Group of Hospital Hygiene Studio) and "*Building Hygiene*" are working and collaborating with several research groups contributing to national and international calls on these relevant issues. This volume aims to provide a number of contributions on indoor air quality in hospitals and in other health facilities where a picture of the current situation is drawn, that is inherent both to the main indoor pollutants, their sources and the risks they generate in hospitals, and, with regards to the comparison between the main international and national legislation and research activities on air quality, on thermal comfort, pollutants concentration and monitoring parameters.

In light of these considerations and currently lacking specific regulatory performance tools for healthcare facilities, this collection of contributions presents through a multidisciplinary approach, practical considerations on the adequate choice of hospital construction site, building materials, finishing and furniture, cleaning products and maintenance activities and up to management strategies. The intent is therefore to provide clear information of proven scientific evidence to all the stakeholders.

Carlo Signorelli
President of S.It.I. (Società Italiana di Igiene
Medicina Preventiva e Sanità Pubblica)
Department of Biomedical, Biotechnological and Translation
Sciences, Università degli Studi di Parma
Parma, Italy
and
Università Vita-Salute S. Raffaele
Milan, Italy

Stefano Capolongo
Coordinator of Working Group "Building Hygiene", S.It.I.
Department of Architecture,
Built Environment and Construction Engineering
Politecnico di Milano
Milan, Italy

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Contents

Contributors

AIA Working Group Italian Association of Aerobiology, Scandicci, Florence, Italy

Roberto Albertini Department of Clinical and Experimental Medicine, University of Parma, Parma, Italy

Lucia Bonadonna Department of Environment and Health, Istituto Superiore di Sanità, Rome, Italy

Alice Borghini Public Health Institute, Hygiene Section, Università Cattolica del Sacro Cuore, Rome, Italy

Rossella Briancesco Department of Environment and Health, Istituto Superiore di Sanità, Rome, Italy

Stefano Capolongo Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Milan, Italy

Anna Maria Coccia Department of Environment and Health, Istituto Superiore di Sanità, Rome, Italy

Maria Luisa Cristina Department of Health Sciences, University of Genoa, Genoa, Italy

Daniela D'Alessandro Department of Civil Building Environmental Engineering, Sapienza Università di Roma, Rome, Italy

Marco De Felice Department of Environment and Health, Istituto Superiore di Sanità, Rome, Italy

Osvalda De Giglio Department of Biomedical Science and Human Oncology—Hygiene Section, University of Bari "Aldo Moro", Bari, Italy

Gaetano Maria Fara Department of Public Health and Infectious Diseases, Sapienza Università di Roma, Rome, Italy

GISIO-SItI Working Group Gruppo Italiano di Studio di Igiene Ospedaliera (Italian Study Group on Hospital Hygiene-Italian Society of Hygiene, Preventive Medicine and Public Health), Rome, Italy

Marco Gola Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Milan, Italy

Cesare Maria Joppolo Department of Energy, Politecnico di Milano, Milan, Italy

Veruscka Mannoni Department of Environment and Health, Istituto Superiore di Sanità, Rome, Italy

Ambra Mele Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Milan, Italy

Maria Teresa Montagna Department of Biomedical Science and Human Oncology—Hygiene Section, University of Bari "Aldo Moro", Bari, Italy

Umberto Moscato Public Health Institute, Hygiene Section, Università Cattolica del Sacro Cuore, Rome, Italy

Ilaria Oberti Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Milan, Italy

Giorgio Padula Department of Environment and Health, Istituto Superiore di Sanità, Rome, Italy

Cesira Pasquarella Department of Biomedical, Biotechnological and Translation Sciences, University of Parma, Parma, Italy

Francesco Romano Department of Energy, Politecnico di Milano, Milan, Italy

Carlo Signorelli Department of Biomedical, Biotechnological and Translation Sciences, Università degli Studi di Parma, Parma, Italy; Università Vita-Salute S. Raffaele, Milan, Italy

SIMPIOS Working Group Italian Multidisciplinary Society for Infection Prevention in Healthcare Facilities, Milan, Italy

Gaetano Settimo Department of Environment and Health, Istituto Superiore di Sanità, Rome, Italy

Adele Anna Teleman Public Health Institute, Hygiene Section, Università Cattolica del Sacro Cuore, Rome, Italy

Barbara Tolino Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Milan, Italy

Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
AHU	Air Handling Unit
AIA	Associazione Italiana di Aerobiologia (Italian Association of Aerobiology)
AIRMEX	European Indoor Air Monitoring and Exposure Assessment Project
AIRP	Associazione Italiana di Radioprotezione (Italian Radiation Protection Association)
AMAS	Active Microbial Air Sampler
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BRI	Building-Related Illness
BTEX	Benzene exposure, Toulene, Ethylbenzene and Xylene
CDC	Centers for Disease Control
CEI	Comitato Elettronico Italiano (Italian Electronic Committee)
CEN	Comité européen de normalisation (European Committee for Standardization)
CFU	Colony Forming Unit
CTI	Comitato Tecnico Italiano (Italian Technical Committee)
DEFRA	Department for Environment, Food & Rural Affairs
DNPH	Dinitrophenylhydrazin
EC	European Commission
ECA	European Collaborative Action
ECA-IAQ	European Collaborative Action—Urban Air, Indoor Environment and Human Exposure
EDC	Endocrine Disrupting Chemical
EEA	European Environmental Agency
ENHIS	Environment and Health Information System
EnVIE	Indoor Air Quality and Health Effect
EPA	Environmental Protection Agency

ERO	European Risk Observatory
EU	European Union
EVD	Ebola Virus Disease
FGI	Facility Guidelines Institute
GdS-ISS	Gruppo di Studio (Research Group) Istituto Superiore di Sanità (Italian Institute of Health)
GISIO	Gruppo Italiano di Studio di Igiene Ospedaliera (Italian Study Group on Hospital Hygiene)
HAI	Hospital acquired infection
HCAI	Health Care-Associated Infection
HEPA	High-Efficiency Particulate Air
HHS	U.S. Department of Health and Human Service
HICPAC	Healthcare Infection Control Practices Advisory Committee
HVAC	Heating, Ventilating, and Air-Conditioning
IAQ	Indoor Air Quality
IARC	International Agency for Research on Cancer
ICRA	Infection Control Risk Assessment
ICU	Intensive Care Unit
IEMB	Indoor Environment Management Branch
IEQ	Indoor Environmental Quality
IMA	Index of Microbial Air contamination
IRIS	Integrated Risk Information System
IRPA	International Radiation Protection Association
ISO	International Organization for Standardization
ISPESL	Istituto superiore per la prevenzione e la sicurezza del lavoro (Italian Institute for prevention and safety in the workplace)
ISS	Istituto Superiore di Sanità (Italian Institute of Health)
LAF	Laminar Air-Flow
LEED	Leadership in Energy and Environmental Design
MERV	Minimum Efficiency Reporting Value
MRSA	Methicillin Resistant Staphylococcus Aureus
NTM	Nontuberculous mycobacteria
OPC	Optical Particle Counter
PACU	Post-Anaesthesia Care Unit
PAH	Polycyclic Aromatic Hydrocarbon
PLA	Plastic Polylactic Acid
PMV	Predicted Mean Vote
POM	Particulate Organic Matter
PPD	Percentage of Persons Dissatisfied
PVC	Poly-Vinyl Chloride
SAS	Surface Air System
SBS	Sick-Building Syndrome
SCHER	Scientific Committee on Health and Environmental Risk
SCOEL	Scientific Committee on Occupational Exposure Limit
SD	Standard Deviation

SIMPIOS	Società Italiana Multidisciplinare per la Prevenzione delle Infezioni nelle Organizzazioni Sanitarie (Italian Multidisciplinary Society for the Prevention of Infection in Healthcare Organizations)
SIPO	Sistema Informativo Progetto Ospedali (Information System Hospital Project)
SItI	Società Italiana di Igiene, Medicina Preventiva e Sanità Pubblica (Society of Hygiene, Preventive Medicine, and Public Health)
SVOC	Semi-Volatile Organic Compound
THADE	Towards Health Air in Dwellings in Europe
TLV	Threshold Limit Value
ULPA	Ultra Low Penetration Air filter
UNI	Ente Italiano di Normazione (Italian National Unification)
UR	Unit Risk
USGBC	US Green Building Council
UTA	Air Treatment Unit
VAV	Variable Air Volume
VLEP	Occupational Exposure Limit Value
VOC	Volatile Organic Compound
VRE	Vancomycin Resistant Enterococci
VVOC	Very Volatile Organic Compound
WHO	World Health Organization

Indoor Air Quality in Healing Environments: Impacts of Physical, Chemical, and Biological Environmental Factors on Users

Stefano Capolongo and Gaetano Settimo

Indoor Air Pollution in Healthcare Facilities

Indoor pollution is defined as "the presence of physical, chemical, and biological contaminants in confined spaces' air does not present in outdoor air of high quality ecological systems" (Ministero dell'Ambiente 1991). Health facilities, places of care, must be aimed to the well-being of all their users but, paradoxically, sometimes they become unhealthy environments with risk of infection (Capolongo et al. 2015).

Indoor air pollution obtains particular importance in public health issues because it is related to many of the major chronic diseases, linked to respiratory, skin, mucous membranes, nervous and immune systems, such as asthma, fever by humidifiers, allergic alveolitis, and legionellosis (Montagna et al. 2007). In addition to these well-known diseases, several symptoms, very frequently characterized by neurosensory effects that determine conditions of discomfort, decreased wellness of occupants, and negative perception of air quality, may manifest. All these pathologies are caused by many aspects related to indoor air quality that affect mainly the vulnerable population (elderly, children, and those who already suffer from chronic diseases).

The main factors of air pollution in healthcare-confined spaces are bacteria, substances used for therapeutic and diagnostic purposes, odors generated by cleaning and maintenance products, disinfectants, heating systems, ventilation and

S. Capolongo (✉)
Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Via G. Ponzio, 31, 20133 Milan, Italy
e-mail: stefano.capolongo@polimi.it

G. Settimo
Department of Environment and Health, Istituto Superiore di Sanità, Viale Regina Elena 299, 00161 Rome, Italy
e-mail: gaetano.settimo@iss.it

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air-conditioning, building materials, furniture and finishing (paints, flooring, etc.). Moreover, the outdoor environment, with its pollutant concentrations, has great effects (Signorelli and Riccò 2012).

From the union of all these factors, the result cannot be considered acceptable and consequently poor ventilation and inadequate air exchange influence negatively the conditions of healthiness. To overcome these criticisms, it is necessary to refer to UNI 10339 regarding the requirements of aeraulic systems (CTI 1995), in Italian context, and internationally to ASHRAE regarding the ventilation in healthcare facilities (ANSI/ASHRAE 2008).

The indoor air quality (IAQ) in a hospital, as any other building, is influenced by the outdoor environment and, therefore, by industries' proximity, road traffic, parking lots, warehouses of irritating substances or waste, construction sites, or any other source of air pollution itself. So, to ensure safety and air quality, it should be considered carefully the location of the outer air intakes of the ventilation systems (de Antonellis et al. 2014).

The persistence of these contaminants within the healing environments affects the indoor air quality compromising wellness and safety conditions that must be fundamentals in an adequate hospital complex (Berrube et al. 2011).

Indoor pollutants' concentration can vary over the time, and it also depends on the typology of the sources, such as ventilation and the activities carried out by the occupants in the areas concerned. Indoor air, often characterized by a mixture of compounds very variable from outdoor one air, can present concentration values of pollutants higher than those of external environment and, sometimes, some indoor pollutants are not detectable outdoor (WHO 1982, 1984; Settimo and D'Alessandro 2014; Settimo 2015).

In Italy, there is no legislation regulating physical, chemical, and biological pollutants' contamination of air in specific hospital areas, but only ISPESL Guidelines (Italian Institute for job's prevention and security) for three environments (surgery, delivery, and emergency departments). But they do not provide concentration limit values; therefore, the Legislative Decree No. 81/2008 is used as a reference document, although it is generic for workplaces (Italia 2008). The decree defines:

- the physical agents (noise, ultrasound, infrasound, vibration, electromagnetic fields, optical radiation, and microclimate);
- values for noise exposure, ultrasonic, electromagnetic fields, optical radiation, and laser radiation limits;
- for dangerous substances the concentration levels of certain chemical and carcinogens pollutants such as benzene, chloride, wood dust, and asbestos;
- for biological agents, such as bacteria, viruses, parasites and fungi, only the control measures, without any specific limits.

Currently, chemical contamination remains the main issue in health care because it is still a field rarely monitored and explored.

Classification of the Main Indoor Pollutants in Healthcare Facilities

WHO in 2010 has developed guidelines for indoor air quality identifying nine dangerous chemical substances (WHO 2010). The guidelines specify some values for air quality inside the buildings and provide a scientific reference for legally enforceable standards in all world's countries and suggesting public health professionals involved in the prevention of environmental exposures' health risks, as well as specialists and authorities involved in design, renovation, and maintenance of buildings, and decision making for indoor materials and products.

The hospital, as public place that welcomes patients with dissimilar health conditions, cultures, and origins, is the building with the highest number of risk factors and indoor air pollutions. In addition to traditional outdoor sources of pollution, occupants, and building factors, it is necessary to add those relating to therapeutic activities and specific medical products (Capolongo 2016).

Since many contaminants can influence air quality in healing environments and sources of chemical, physical, and biological pollutants are many. It is fundamental to ensure an adequate air change through proper design of air-conditioning and ventilation. In the same time it must ensure to introduce the best outdoor air, minimize pollution related to materials, products and activities, dilute the pollutants' concentration, and then drain them (Leung and Chan 2006).

So all these agents, if not properly eliminated, are likely to worsen the conditions of well-being and increase the risk of infection. As several authors state, indoor air quality and contaminants' absence constitute the principle of quality and safety that a healthcare facility must possess (Santarsiero et al. 2014).

Risk Factors and Health Effects

Indoor air quality is decisive for users' well-being in a healthcare facility. The hospital is not only a workplace but also, above all, a structure in which citizens confide in quality and health services; therefore, it must be a safe place where the assessment of risk factors is paramount for the quality of the hospital and services provided (Capolongo et al. 2015).

Hospitals incorporate a variety of risks that can be divided into *physical*, *chemical, and biological risks*.

Physical Risk Factors

Physical risk factors in healthcare facilities are due:

- to *microclimatic parameters* (temperature and relative humidity), as they are fundamental parameters, not only for thermal comfort, but also because high

temperatures facilitate the spread of gaseous substances emanating from furnishings and furniture, medicinal and cleaning products, and because humidity below 20% increases the presence of dust in air, bacteria in suspension and possible electrical charges, and with values greater than 60%, related to high temperatures and inadequate air changes, it determinates the proliferation of germs, presence of rot, mold, and condensation on cold walls, causing discomfort and health risks;

- to *ionizing radiations*, as in the health issues they represent a fundamental role in diagnosis and therapy; in fact, they are generated by radiology, diagnostic radiology, and nuclear medicine activities. This typology of radiations interacts with materials in the proximity by depositing on them their energy. This energy in organic tissues causes a biological damage that can be divided into three main categories: radiation burn (or deterministic health effects), stochastic health effects, and stochastic genetic health effects; the first two are those which affect persons irradiated, and the genetic ones, instead, affect their descendants. The purpose of ISPESL and AIRP (Italian Association of Radiation Protection, related to the International Radiation Protection Association), with the "Operative Manual for radiation protection in medical activities," is to assess and prevent, or at least limit, biological damage to both workers exposed and the population (ISPESL and AIRP 2003);
- to *nonionizing radiation*s or *electromagnetic fields*, whose energy is too low to break atomic bonds and ionize the matter. They include ultraviolet rays, visible radiation, infrared, microwaves, radio frequencies, electromagnetic fields, and extremely low-frequency, static, electric, and magnetic fields. The acute health effects occur in the immediate or short term, while chronic ones affect in successive periods of time exposure;
- to *manual handling of loads and patients*.

Chemical Risk Factors

Chemical risks are related to air pollution and they are as follows:

- *Carbon Monoxide* (CO), which is an odorless, colorless, and tasteless gas, highly toxic at low concentrations that causes fatigue and pains in the chest for heart patients; at moderate concentrations of coordination problems, headaches, nausea, dizziness, etc., and, on the contrary, at very high concentrations, it is lethal. The sources that generate it are incomplete combustion of materials containing carbon (heating) and the malfunction of the gas-heating systems, stoves, furnaces, and fireplaces, inadequate ventilation; and also the proximity to roads with high vehicular traffic and garage and parking lots; and these can cause a significant impact on the gas concentrations in confined environments (Nyhan et al. 2016);

- *Nitrogen Dioxide* (NO_2), which is a toxic gas with yellow red color and a strong and pungent odor; it is a highly reactive and corrosive oxidant and, with great irritant power, it causes disturbances to the lower respiratory system and susceptibility to infections, especially in people with lung diseases. It is generated by high-temperature combustion processes (cooking stoves, heating systems with internal boilers, etc.). The proximity to roads with high vehicular traffic and parking garages can significantly affect gas concentrations in indoor environments because NO_2 is contained in exhaust gases of motor vehicles;
- *Sulfur Dioxide* (SO_2) is colorless, nonflammable, and highly soluble in water gas, with a pungent smell; it causes irritation to skin, eyes, and mucous membranes and contributes to asthma, bronchitis, and tracheitis. This also is produced by combustion processes;
- Volatile Organic Compounds (VOCs) are a set of liquid or vapor substances. Among the most common compounds, there are some aldehyde hydrocarbons, including formaldehyde. They cause eyes, nose, and throat irritations, as well as headache, nausea, and fatigue; chronic effects include kidney, liver, and central nervous system's damages, and, in extreme cases, cancer. The main sources that emit VOCs are paints, lacquers, pesticides, cleaning products, construction materials, and office supplies such as stickers, markers, printers, and copiers;
- *Formaldehyde* is a colorless gas with a characteristic pungent odor and a strong irritating power to mucous membranes, eyes, and respiratory system. It causes conjunctivitis, asthma, contact dermatitis, fatigue, anxiety, headaches, nausea, drowsiness, and dizziness; it is mutagenic and carcinogenic. It is attributable to furniture, fabrics, construction materials, in tobacco smoke, and in many everyday products, such as detergents, dyes, disinfectants, plastics, glues, and paint materials;
- *Benzene* is an aromatic hydrocarbon with a pungent and sweet smell that evaporates in air very quickly as all VOCs, and it is a highly flammable substance. At lower levels of concentration, benzene can cause dizziness, drowsiness, increased heart rate, tremors, confusion, and unconsciousness. Prolonged concentrations over time can impair memory and some psychic abilities as well as causing disturbances and irritant effects on skin and mucous membranes; it is also a human carcinogen. It comes from cigarette smoke, incomplete combustion of domestic coal, and oil and vapors released from products that contain it, such as glues, paints, furniture and floor wax, and cleaning agents (Manzoli et al. 2016);
- *Polycyclic Aromatic Hydrocarbons* (PAHs) are a group of organic compounds with two or more condensed benzene bands. They cause irritation to the respiratory system and many of them are carcinogenic. They are generated by wood stoves, fireplaces, food cooked over the flames or smoke smoked and tobacco smoke. They are deposited on shoes and clothing from the outdoor environments;
- *Ozone* (O_3) is a poisonous gas, with a penetrating odor and pale blue. It is present in troposphere and contributes to air pollution; it is harmful to humans

and environment. As a powerful oxidant, it attacks the organic tissues of the respiratory system, causing breathing disturbances and aggravating asthma episodes. It is emitted by photocopiers, laser printers, ultraviolet lamps, and some air purifiers;

- *particulates* (PM_{10} and $PM_{2.5}$) are constituted by all those solid, liquid, and aerosol particles, with an adequate diameter and weight such as to remain suspended in the air. It may cause irritating and harmful effects to the respiratory system, obstruction of the *pulmonary alveoli*, heart diseases, and the possibility of inducing alterations in the immune system. It is generated by cigarette smoking, burning, outdoor environment, spray, cooking food, bacteria, spores, pollen, and human activities (Bessonneau et al. 2013; Settimo et al. 2016).

Biological Risk Factors

Regarding biological risks, they are related to the presence of microorganisms (fungi, bacteria, viruses, parasites, protozoa, etc.), dust mites, animal- and plant-derived allergens found in the air, in the dust, in construction materials and furniture, in engineering plants' water, and air-conditioning. It is mainly influenced by physical factors, such as humidity and temperature. Individuals potentially exposed to this risk include all age groups, in particular the most vulnerable ones, such as children and elderly (D'Alessandro et al. 2015, 2016).

The health effects caused by the presence of organic contaminants can be classified into three types: infectious, toxic, and allergic ones, and they may occur with different intensities in relation to various factors, including physical conditions and the susceptibility of each individual.

The biological risk in healthcare facilities can be controlled and reduced through interventions of both structural and engineering plants' actions and in respect of basic hygienic and behavioral knowledge by facility managers, workers, and users (D'Alessandro et al. 2016).

When this risk is not well managed and monitored, infectious risks can arise, affecting several categories of people involved in the hospital, which contaminate directly, through the respiration of biological agents (bacteria, viruses, fungi, endotoxins, spores, etc.), their physique (Cabo Verde et al. 2015; Montagna et al. 2014).

In Italian hospitals' context, every year 25,000 people die from hospital infections, while in the USA despite the technological level of health facilities is the highest one, over 100,000 people die each year from hospital infections (Capolongo et al. 2015; Montagna et al. 2007).

In Italy, to try to overcome this criticism, ISPESL drew up some guidelines on safety and hygiene standards in operating room, delivery room, and emergency room, analyzing for each of these environments physical, chemical, and biological risks, focusing only on some contaminants (Italia 2008; ISPESL 2005a, b, 2009).

All these risk factors do nothing but increase indoor pollution, which is considered one of the most important risk factors in healing environments, because it is generated from numerous traditional pollution sources and also by the hospital activities (Aurigemma et al. 2010).

User Categories Subjected to the Risk Factors

The possibility of being exposed to the risks mentioned previously affects different categories of users, because being a public facility, there are hospital and technical staffs, the inpatients, outpatient users, and visitors. All of these categories may be more or less at risk according to the time of permanence in the hospital, which can be long, medium, or short in relation to the users' state of health and age (Capolongo et al. 2016). Therefore, safety issues do not only affect workers' category, as in the main workplaces, but indirectly it is also extended to all patients and visitors, who may react differently to the same conditions.

It is also not desirable to evaluate individual exposure risk, as the danger of polluting agents is given by the time of exposure, by the chemical composition, and by their combination.

Among the groups particularly at risk are considered both patients (especially elderly) that remain in the healthcare facility for several days, weeks, or months, because they have reduced immunity, and hospital staff, which for all the activities they perform, is subject to numerous risks such as infections, wounds, accidents, but above all is more heavily exposed to indoor pollution of physical and chemical risk factors, because unlike the patients, they are in close contact with hazardous chemical substances for a prolonged period of time and use complex technologies (Agodi et al. 2013; Meneghini 2007).

Management and Risk Assessment

The hospital incorporates a multitude of risks and environments, and it has a considerable differentiation of users, not only in terms of workers, but also such as patients, relatives, visitors, external companies, and students; then to dispense the entire system throughout the day all the services at the highest efficiency level, it is necessary to monitor safety aspects and implement the risk assessment, which must be extensive, thorough, detailed, and made by people expert in the fields of organization and management of healing environments. In Italy, the risk assessment in health care is established by the Legislative Decree No. 81/2008, which regulates generally safety in workplaces (Italia 2008).

The decree concerns physical, chemical, and biological agents providing maximum concentration limits; in particular, Title IX regards chemical risks for the medical staff in close contact with chemical substances, such as anticlastic

(professional exposure) while for all the other users it refers to WHO guidelines on IAQ (WHO 2010; Settimo 2015) and the Legislative Decree No. 155/2010, which regulates outdoor air pollution (Italia 2010).

From the regulatory point of view, Art. 17 of Legislative Decree no. 81/2008 identifies the employer as the responsible for the risk assessment: This function turns out to be nondelegable. The employer benefits from the advice of experts in the field, such as security and protection manager and workers, the competent doctor, and the chief medical officer, professionally responsible for their actions.

Before estimating risk assessment process, it is essential that the employer is fully aware of the number of all direct employees, all the external companies or collaborating cooperatives, their duties and activities, and all the healing environments usually frequented. He must possess all the updated hospital plans, the intended use of the rooms and all the engineering plans available, and, in addition, the list of equipment, machines, and devices.

This assessment is useful if it is thorough, detailed, and carried out by competent professionals. If it is carried out by externals fragmentary or similar, in part or in entirely, to several healing environments with similar processes, it often turns out to be merely an application of the legislation without reaching correctly the ultimate objective, the safety.

Often, there is confusion: risk assessment is not the ultimate goal, but the starting point for the employer in order to implement measures to improve security and health conditions of workers and the workplaces. In the process of the assessment, it is therefore crucial the choice of active actors, particularly the security and protection manager and the competent doctor, and the performance of their duties must take into account the basic rules, in particular in hospitals:

- clear distinction between the responsibilities and areas of competence of security and protection manager, the competent doctor and the chief medical officer;
- clear identification of managers and safety officers in all areas, even common ones (lobbies, corridors, waiting rooms, staircases, entrances, gardens, parking, etc.); and
- clear separation of areas of competence in the case of university hospitals (Gray et al. 2012).

Moreover, risk assessment is the starting point to be able to program improvement measures in order to prevent or reduce the risks, accidents, or injuries with flexibility (Astley et al. 2015). It must take account of changes which in turn may have led to a reduction or an increase in workplaces' risk (D'Alessandro et al. 2013).

The improvement program, as a result of the risk assessment, naturally must take into account the organizational, technical, and economic aspects of the hospital itself. Programming an intervention means to identify the priorities in accordance with local regulations, to deal with the criticism and to make efforts to find a solution compatible with the medical organization, economic issues, and available techniques.

All the improvements in safety area will also improve the functioning, quality, symbol, and productivity of the entire architecture for health. The process of continuous improvement requires above all the will of the employer, the maximum involvement of all parties, a cyclicity of the shares in order to plan interventions and whether those have actually made an improvement in the health and safety conditions at workplaces.

Even the workers, properly trained and informed, can contribute to the security process informing the employer through the representatives of workers' safety, for special needs, anomalies, and improvements. Every employee must be sensitized and empowered on the hygiene and safety of the activities and workplaces; only when all the hospital staff (doctors, nurses, maintenance, cleaning companies, bar, canteen, etc.) has been properly trained and informed on the rights and duties, risks, possible procedures to follow, the work of the employer, the safety and protection manager, and competent doctor can be much more effective (D'Alessandro et al. 2014). Naturally, the hospital reaches a better organization when each worker knows what to do on any occasion or knows where to turn, and by what means to any activity, process, editing, documentary research, etc.

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Existing Guidelines for Indoor Air Quality: The Case Study of Hospital Environments

Gaetano Settimo

Introduction

In Europe, exposure to organic and inorganic chemical pollutants and their related health aspects in indoor spaces, such as homes or shared communities (e.g. schools, hospitals, day care, sports facilities, libraries, restaurants, theatres, cinemas and public transport), has been taken into increasing consideration by the general public, governments and, in particular, by the main environmental and health institutions (WHO 1982, 1984, 2000).

The hospitals and first-aid/healthcare centres can be ranked among indoor environments. In such structures, different activities take place, such as research, diagnosis, teaching and training, rehabilitation and prevention (Astley et al. 2015; Alfonsi et al. 2014). About 10% of workers in European Union belong to the health and welfare sector, and many of them work in hospitals (EC 2010).

Therefore, a variety of persons recognizing different exposure risks (professional vs. non professional exposure, and associated sensitivity and vulnerability) share the same indoor environment, such as students, physicians, nurses, young and old patients and visitors (WHO 1982; Buffoli et al. 2007; Capolongo et al. 2015a).

Within this frame, dedicated guidelines and standard operating procedures were already issued on professional exposure in healthcare centres, according to the specific work duty in the different units [i.e. surgery unit, antineoplastic unit and sterilization/sanitization service (Capolongo 2016)].

G. Settimo (✉)
Department of Environment and Health, Istituto Superiore di Sanità,
Viale Regina Elena 299, 00161 Rome, Italy
e-mail: gaetano.settimo@iss.it

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Until now, for the administrative staff, training and teaching personnel, patients and visitors, biological hazards and related risks have been mainly taken into account, and only recently, the chemical agents released from indoor sources as consequence of the anthropogenic activities have been considered (D'Alessandro et al. 2016; Capolongo et al. 2015a).

Exposure to indoor chemical compounds of anthropic origin may contribute significantly to a population's and workers' overall intake of pollutants. As a result of a long-term work from 1970s (Suess 1992), WHO has shifted from devoting a chapter in its air quality guidelines on indoor air pollutants, mainly associated with radon and environmental tobacco smoke (WHO 1987, 1999, 2000, 2006) and with specific indoor air quality guidelines (WHO 2009, 2010). These guidelines cover various pollutants such as benzene, nitrogen dioxide, polycyclic aromatic hydrocarbons (e.g. benzo[a]pyrene), naphthalene, carbon monoxide, radon, trichloroethylene and tetrachloroethylene (WHO 2010) and also mould and dampness (WHO 2009).

The European Environmental Agency (EEA) highlights that the quality of air inside buildings is affected by the quality of ambient air, construction materials, air circulation, electrical appliances, cleaning products used, habits of occupants, such as smoking, and by building's upkeep (such as energy-saving steps) (EEA 2010, 2013). A vast range of pollutants, with different patterns of dispersion, can concentrate on indoor environments in relation not only to the outdoor concentrations but also to the activities carried out by individuals, to the presence of pets, to the use of furniture and construction materials, as European Collaborative Action "Urban Air, Indoor Environment and Human Exposure" stated (ECA-IAQ 2012).

In the past twenty-five years ago, the European commission (EC) has also funded numerous projects, for example the THADE project "Towards Health Air in Dwellings in Europe" (2002–2004) (Franchi et al. 2004), the EnVIE project "Indoor Air Quality and Health Effects" (de Oliveira Fernandes et al. 2010), the AIRMEX project "European Indoor Air Monitoring and Exposure Assessment Project" (2003–2008) (Kotzias et al. 2005, 2009) and the EXPOLIS study (1996–2000). All these projects have attempted, at least partially, to increase awareness on indoor air quality and definition of priorities and objectives (Coulson et al. 2005).

At the European level, there is a trend for an integrated promotion of the quality of indoor air in order to drastically reduce the presence of pollutants of various kinds; but regulations in various European member states are still absent.

Through discussing a national case, it is possible to consider all the norms and legal reference values that are currently available in Europe for indoor air quality (Settimo 2012, 2013, 2015; Oppio et al. 2016). All the norms and references available in Europe constitute a framework that can provide support in case of absence of national legislation and, in any case, a legislation is going to be organized.

Limit Values and Technical Recommendations

Although norms on indoor air pollution in various European member states are still absent, there are various reference values available in many states (Table 1). It is important and necessary to proceed soon to a harmonization by establishing the elements (such as collection and analysis methods) as well as the parameters which need to be considered for indoor air pollution control. This means to review according to established protocols the available information, gathered in a systematic way, on the quantity, nature and origin of pollutants. In this respect, the European Regulatory Committee (CEN) and International Organization for Standardization (ISO) have provided a set of specific instructions on standard operating procedures for indoor air quality monitoring (ISO 16000). The EC within the European Collaborative Action (ECA) has carried out a multidisciplinary collaboration among experts, producing a collection of 27 specific papers, published between 1988 and 2012.

In terms of harmonization, important information is also available at WHO for drafting the indoor air quality guidelines, for which evidence on health effects is considered reasonably certain (WHO 2010). WHO guidelines have taken into consideration the following: benzene, nitrogen dioxide, polycyclic aromatic hydrocarbons (especially benzo[a]pyrene), naphthalene, carbon monoxide, radon, trichloroethylene and tetrachloroethylene.

Regarding cancerogenous pollutants in the air, WHO provides risk assessment for the general population. The guidelines constitute a base for establishing legal norms (and limits), adopted by various states, subject to periodic revision. However, the guidelines related to airborne pollutants are quite limited due to the large number of indoor airborne pollutants, and this has lead to a proliferation of norms and reference values that constitute a peculiar European framework.

Currently, we are far from the past situation when industrial occupational exposure limit values were used to assess non-industrial indoor air quality in case of absence of reference values, a practice already considered inappropriate by WHO (1982).

Reference values allowed for indoor environments are more restrictive than those suggested for workplaces, based on 8-h a day, 5-day a week exposure and for a maximum period of 40 years, and targeted to the protection of workers against professional illnesses (WHO 2010; Italy 2008).

Moreover, it is worth considering European reference documents drafted by standardization agencies, such as the CEN and the ISO. Such organizations have long been involved in researching the best technical solutions regarding the methodologies for conducting tests (sampling, analysis and measurement). Currently, the EN norms can provide support for indoor air pollution monitoring and reduction. In fact, all of the previously listed EN norms have been ratified in Italy by the Italian National Board of Unification (UNI). The main norms on measurement of indoor air quality parameters that can be identified are thirty-three.

Table 1 Guidelines for air quality[a] and for individual risk in different European states issued by WHO[b] regarding certain pollutants (Settimo 2015; D'Alessandro and Capolongo 2015)

µg/m^3	WHO ambient air	WHO indoor air	French	German	Netherlands	UK	Belgium	Finland[c]	Austrian	Portugal	Norway	Poland home	Poland public office
Benzene	No guidelines values 6×10^{-6} $(\mu g/m^3)^{-1}$ (UR/lifetime) 1.7 µg/m^3 (UR/lifetime) 10^{-6} 17 µg/m^3 (UR/lifetime) 10^{-5}	No guidelines values 6×10^{-6} $(\mu g/m^3)^{-1}$ (UR/lifetime) 1.7 µg/m^3 (UR/lifetime) 10^{-6} 17 µg/m^3 (UR/lifetime) 10^{-5}	30 µg/m^3 (1 Daily–1 year) 10 µg/m^3 (1 year) da UR WHO: 0.2 µg/m^3 (UR/lifetime) 10^{-6} 2 µg/m^3 (UR/lifetime) 10^{-5} 5 by 1 January 2013 2 by 1 January 2016	–	20	5 (1 year)	≤2 10	–	–	5 (8 h)	–	10 (24 h)	20 (8 h)
Formaldehyde	100 (30 min)	100 (30 min)	50 (2 h) 10 (1 year) 30 by 1 January 2018, 10 by 1 January 2023	12	120 (30 min) 10 (1 year) 1.2 year-long exposure	100 (30 min)	≤10 (30 min) 100 (30 min)	50	100 (30 min 60 (24 h)	100 (8 h)	100 (30 min)	50 (24 h)	100 (8 h)
Carbon monoxide mg/m^3	100 (15 min) 60 (30 min) 30 (1 h) 10 (8 h)	100 (15 min) 35 ((1 h) 10 (8 h) 7 (24 h)	100 (15 min) 60 (30 min) 30 (1 h) 10 (8 h)	60 (30 min) 15 (8 h)	100 (15 min) 60 (30 min) 30 (1 h) 10 (8 h)	100 (15 min) 60 (30 min) 30 (1 h) 10 (8 h)	5.7 (24 h) 30 (1 h)	8	–	10 (8 h)	25 (1 h) 10 (8 h)	25 (1 h)	10 (8 h)
Nitrogen dioxide	200 (1 h) 40 (1 year)	200 (1 h) 40 (1 year)	200 (1 h) 40 (1 year)	350 (30 min) 60 (week)	200 (1 h) 40 (1 year)	300 (1 h) 40 (1 year)	≤135 (1 h) 200 (1 h)	–	–	–	200 (1 h) 100 (24 h)	–	

(continued)

Table 1 (continued)

µg/m^3	WHO ambient air	WHO indoor air	French	German	Netherlands	UK	Belgium	Finland[c]	Austrian	Portugal	Norway	Poland home	Poland public office
Naphthalene	–	100 (1 year)	10 (1 h)	20–200 (week)	25	–	–	–	–	–	–	100 (24 h)	150 (8 h)
Styrene	260 (week) 70 (30 min)	–	–	30–300 (week)	900	–	–	–	40 (week) 10 (1 h)	–	–	20 (24 h)	30 (8 h)
Polycyclic aromatic hydrocarbons PAH (BaP) ng/m^3	No guidelines values 8.7×10^{-5} (µg/m^3)$^{-1}$ (UR/lifetime) 0.12 ng/m^3 (UR/lifetime) 10^{-6} 1.2 ng/m^3 (UR/lifetime) 10^{-5}	No guidelines values 8.7×10^{-5} (µg/m^3)$^{-1}$ (UR/lifetime) 0.12 ng/m^3 (UR/lifetime) 10^{-6} 1.2 ng/m^3 (UR/lifetime) 10^{-5}	–	–	1.2	0.25 (1 year)	–	–	–	–	–	–	–
Tetrachloroethylene	250 (1 year)	250 (1 year)	1380 (1–14 days) 250 (1 year)	1 (week)	250	–	≤100	–	250 (week)	250 (8 h)	–	–	–
Trichloroethylene	No guidelines values 4.3×10^{-7} (µg/m^3)$^{-1}$ (UR/lifetime) 23 µg/m^3 (UR/lifetime) 10^{-6} 230 µg/m^3 (UR/lifetime) 10^{-5}	No guidelines values 4.3×10^{-7} (µg/m^3)$^{-1}$ (UR/lifetime) 23 µg/m^3 (UR/lifetime) 10^{-6} 230 µg/m^3 (UR/lifetime) 10^{-5}	800 (14 days–1 year) da UR WHO: 2 µg/m^3 (UR/lifetime) 10^{-6} 20 µg/m^3 (UR/lifetime) 10^{-5}	1 (week)	–	–	≤200	–	–	25 (8 h)	–	150 (24 h)	200 (8 h)
Dichloromethane	3000 (24 h) 450 (week)	–	–	200–2000 (24 h)	200 (1 h)	–	–	–	–	–	–	–	–

(continued)

Table 1 (continued)

µg/m^3	WHO ambient air	WHO indoor air	French	German	Netherlands	UK	Belgium	Finland[c]	Austrian	Portugal	Norway	Poland home	Poland public office
Toluene	260 (week) 1000 (30 min)	–	–	300–3000 (1–14 days)	200 (1 h)	–	≤260	–	75 (1 h)	250 (8 h)	–	200 (24 h)	250 (8 h)
Volatile organic compounds VOC	–	–	–	–	200 (1 h)	–	≤200	–	–	600 (8 h)	400	400	–
PM_{10}	50 (24 h) 20 (1 year)	–	50 (24 h) 20 (1 year)	–	50 (24 h) 20 (1 year)	–	≤40 (24 h)	50	–	50 (8 h)	90 (8 h)	90 (8 h)	–
$PM_{2.5}$	25 (24 h) 10 (1 year)	–	25 (24 h) 10 (1 year)	25 (24 h)	5 (24 h) 10 (1 year)	–	≤15 (1 year)		–	25 (8 h)	40 (8 h)	40 (8 h)	–

Notes

[a]Guidelines of the quality of indoor air report levels of concentration of pollutants in air, for exposure times indicated, for which no adverse effects on health are expected, concerning substances which are not cancerogenous

[b]The assessment of the increase in unitary risk (Unit risk-UR) refers to the additional risk of cancer, which could take place in a hypothetical population in which all individuals are continuously exposed, from birth for their entire life, to a concentration of the risk factor in the air they breathe

[c]The guidance values for indoor environments are valid under the following frame: space taken up at least 6 month long, with the venting systems turned on in continous

The European Framework

When national norms providing guidelines or reference values to be used for assessment activities are not available, it is possible to refer to criteria and norms adopted in other states or apply the ones available in the scientific literature, or by analogy, other standards such as those relative to ambient air (EU 2008).

In addition, several European states in these last few years have created working groups responsible for drafting the indoor air quality guidelines (Table 1). In the France, Finland, Poland, Portugal and Austria, the recommended guidelines values have legal validity because they have been adopted in legislative acts; on the contrary, in Germany, the Netherlands and UK, the recommended guidelines do not have legal validity but can be used in assessing and improving the quality of indoor air.

Currently, in France the new "Plan d'action sur la qualitè de l'Air Interieur", published in 2013, indicates a series of measures, including also anticipates the requirement of indoor monitoring in hospital and healthcare facilities. It was originally scheduled for 2023.

Methods are a fundamental aspect, as well as the reference values. In all countries, the reference values proposed are related to the methods of sampling and analysis developed by national authorities, for example by the German Institute for Standardization-DIN, Association Française de Normalisation-AFNOR, Bureau de Normalisation-NBN, Finnish Standards Association SFS, Austrian Standards Institute-ASI, Netherlands Instituut Normalisatie-NEN, British-BSI Standards.

So it is possible to consider the existence of a European framework if we summarize the main figures add significant details, regarding the pollutants taken into consideration in guidelines by national countries and WHO, as Table 1 shows.

In Italy, there is not a specific law on indoor air quality, but in recent years, awareness in indoor issues has grown considerably, and specific working groups were activated to address this issue. Already in 1983, the issue of formaldehyde was a matter of concern, and the Ministry of Health suggested, experimentally and temporarily, a maximum concentration limit of 0.1 ppm (0.124 mg/m^3) in neighbourhoods and homes (Ministero della Salute 1983). More recently, the Italian Ministry of Health (Ministero della Salute 2012) has pointed out that indoor air pollution, in non-industrial places but for home, leisure, work and transportation, is an important issue for public health, with major social and economic implications. The report also states that indoor pollutants can be present in concentrations such that while not causing acute effects, they can produce negative effects on human health, especially if linked to prolonged exposure (Ministero della Salute 2012).

Although a law on indoor air pollution does not exist, there are two agreements in force (Italia 2010, 2001). Such agreements, thought far from providing information on timing and procedures to be used regarding limits or standards to be adopted, may nevertheless represent a useful contribution to the enactment of guidelines and to the identification of reference collection and analysis techniques.

So far, in Italy or other European countries, in the absence of a reference legislation information, reference values for indoor air pollution are those available in

the scientific literature or norms adopted in other European states or by analogous standards, for example for ambient air.

The application of standards developed in other European countries can also help overcoming difficult situations for monitoring institutions. Reference values represent an important parameter to be used in the risk assessment.

For example, the Italian National Health Institute (Istituto Superiore di Sanità—ISS) has activated a national research group (GdS-ISS) with representatives of various agencies, such as Ministry of Health, Ministry of Environment, Ministry of Labor and Social Policy, regions and several research institutes to provide scientific support for fine-tuning the guidelines for an appropriate control strategy of indoor spaces. The GdS-ISS has developed eight reference documents on strategies for:

- monitoring strategies for volatile organic compounds (VOCs) in indoor environments (Fuselli et al. 2013a, b);
- monitoring strategies of biological air pollution in indoor environments (Bonadonna et al. 2013);
- workshop. Issues related to indoor air pollution: current situation in Italy. Istituto Superiore di Sanità. Rome, 25 June 2012. Proceedings;
- workshop. Indoor air quality: current national and European situation. The expertise of the National Working Group on indoor air (Santarsiero et al. 2015a, b);
- monitoring strategies to assess the concentration of airborne asbestos and man-made vitreous fibres in the indoor environments (Musmeci et al. 2015);
- microclimate parameters and indoor air pollution (Santarsiero et al. 2015a, b);
- presence of CO_2 and H_2S in indoor environments: current knowledge and scientific field literature (Settimo et al. 2016a, b);
- monitoring strategies to PM_{10} and $PM_{2.5}$ in indoor environments: characterization of inorganic and organic micropollutants (Settimo et al. 2016a, b).

These documents represent a set on how to operate in these environments, the choice of sampling points, techniques, storage and analysis, and determination of other parameters such as, air speed, temperature and the relative humidity. Other factors such as vulnerability of the population and exposure conditions are surely fundamental elements that need to be known for a proper comprehension of the problem. Related to this issue, it has to be considered that the Scientific Committee on Health and Environmental Risks (SCHER) of the European Commission (EU 2007) suggests that the risk assessment be focused on more vulnerable groups such as children, pregnant women, the elderly (over 65), people suffering from asthma, other respiratory or cardiovascular diseases, following a “case-by-case” approach.

Conclusions

Since many years, problems from exposure to indoor air pollutants have been a matter of concern for national as well as European Union legislators, and an increasing numbers of states have been addressing the need for policies regarding health and strategy through specific studies.

The European Union has often addressed the importance to measure and assess indoor air quality, the relative impact on health and possible recommendation regarding future measures (EC 2002; Capolongo et al. 2015a, b).

In-depth knowledge of hygienic-sanitary aspects' assessment of indoor environments is quite important, especially regarding organic and inorganic pollutants, even though the possible levels present in the various spaces are already well known. In order to satisfy the needs for evaluating and controlling indoor spaces, the CEN and ISO have started working on a whole series of specific norms, enacting the ISO 16000 (Table 2).

In some countries (German, the Netherlands, UK), specific guideline values for IAQ have been processed, and they represent reference values and provide methods for sampling and analysis to be used in control and assessment situations (the Netherlands 2007). In other countries (France, Belgium, Finland, Poland), such procedures are already in force through the institution of mandatory monitoring and are periodically applied by public control organs specifically created (France 2011a, b).

Table 2 UNI, CEN and ISO norms on the measurement of IAQ parameters

ISO 16000 indoor air	
Published standards	
Part 1	General aspects of sampling strategy
Part 2	Sampling strategy for formaldehyde
Part 3	Determination of formaldehyde and other carbonyl compounds—active sampling method
Part 4	Determination of formaldehyde—diffusive sampling method
Part 5	Sampling strategy for volatile organic compounds (VOCs)
Part 6	Determination of volatile organic compounds in indoor and test chamber air by active sampling on Tenax TA sorbent, thermal desorption and gas chromatography using MS/FID
Part 7	Sampling strategy for the determination of airborne asbestos fibre concentrations
Part 8	Determination of local mean ages of air in buildings for characterizing ventilation conditions
Part 9	Determination of the emission of volatile organic compounds from building products and furnishing—emission test chamber method
Part 10	Determination of the emission of volatile organic compounds from building products and furnishing—emission test cell method

(continued)

Table 2 (continued)

ISO 16000 indoor air	
Published standards	
Part 11	Determination of the emission of volatile organic compounds from building products and furnishing—sampling, storage of samples and preparation of test specimens
Part 12	Sampling strategy for polychlorinated biphenyls (PCBs), polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs) and polycyclic aromatic hydrocarbons (PAHs)
Part 13	Determination of total (gas- and particle-phase) polychlorinated dioxin-like biphenyls and polychlorinated dibenzo-p-dioxins/dibenzofurans—collection on sorbent-backed filters with high-resolution gas chromatographic/mass spectrometric analysis
Part 14	Determination of total (gas- and particle-phase) polychlorinated dioxin-like biphenyls (PCBs) and polychlorinated dibenzo-p-dioxins/dibenzofurans (PCDDs/PCDFs)—extraction, clean-up and analysis by high-resolution gas chromatography/mass spectrometry
Part 15	Sampling strategy for nitrogen dioxide (NO_2)
Part 16	Detection and enumeration of moulds. Sampling of moulds by filtration
Part 17	Detection and enumeration of moulds. Culture-based method
Part 18	Detection and enumeration of moulds. Sampling by impaction
Part 19	Sampling strategy for moulds
Part 20	Detection and enumeration of moulds—sampling from house dust
Part 21	Detection and enumeration of moulds—sampling from materials
Part 22	Detection and enumeration of moulds—molecular methods
Part 23	Performance test for evaluating the reduction in formaldehyde concentrations by sorptive building materials
Part 24	Performance test for evaluating the reduction in volatile organic compounds (except formaldehyde) concentrations by sorptive building materials
Part 25	Determination of the emission of semi-volatile organic compounds by building products—microchamber method
Part 26	Sampling strategy for carbon dioxide (CO_2)
Part 27	Standard method for the quantitative analysis of asbestos fibres in settled dust
Part 28	Sensory evaluation of emissions from building materials and products
Part 29	Test methods for VOC detectors
Part 30	Sensory testing of indoor air
Part 31	Measurement of flame retardants and plasticizers based on organophosphorus compounds—phosphoric acid ester
Part 32	Investigation of buildings for the occurence of pollutant
Part 33	Determination of phthalates with gas chromatography/mass spectrometry (GC-MS)
Standard under development	
Part 34	General strategies for the measurement of airborne particles
Part 35	Measurement of polybrominated diphenylether, hexabromocyclododecane and hexabromobenzene

(continued)

Table 2 (continued)

Standard under development	
Part 36	Test method for the reduction rate of airborne bacteria by air purifiers using a test chamber
Part 37	Strategies for the measurement of $PM_{2.5}$
Published standards	
UNI EN ISO 16017 Indoor, ambient and workplace air. Sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/capillary gas chromatography	
Part 1	Pumped sampling
Part 2	Diffusive sampling
UNI EN 13779	Ventilation for non-residential buildings: Performance requirements for ventilation and room-conditioning systems
UNI EN 14412	Indoor air quality: Diffusive samplers for the determination of concentrations of gases and vapours. Guide for selection, use and maintenance
UNI EN 15242	Ventilation for buildings: Calculation methods for the determination of air flow rates in buildings including infiltration
UNI EN 15251	Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics

It is crucial that countries that lack national guidelines in the near future manage to adhere, through the promotion of specific programmes and through a coordination of various agencies, to the objectives of the European Community (Jantunen et al. 2011). Currently, for example, in Italy, specific legislation on reference values on IAQ is absent, and this implies the need to use reference values, criteria or standards adopted in other countries or to use values from the scientific literature or, by analogy, use other standards, such as those relating to the ambient air (WHO 1982, 1984, 2000, 2006; Capolongo et al. 2016). In Italy, as well as many other countries, it is necessary to provide guidelines and reference values in accordance with the WHO guidelines for the IAQ (WHO 2010).

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Applications of IAQ Monitoring in International Healthcare Systems

Marco Gola, Ambra Mele, Barbara Tolino, and Stefano Capolongo

The attention to indoor air quality (IAQ) is required especially in all the contexts which host a large number of users because air contaminated can cause severe irritations. Air pollution by ozone and airborne particles and indoor air pollution by VOCs and tobacco smoke are some of the factors related to the appearance of asthma. The suspended particles are considered one of the most critical air pollutants.

IAQ in hospitals is determined by the air quality that enters into the building, the number of occupants, their physical activity with the consequent generation of aerosols, and efficiency of ventilation. Among these, the relative humidity can also have an important contribution to poor IAQ and it is well known as one of the few parameters that can negatively affect the perception of indoor air (Fang et al. 1999).

In addition to the sources of indoor air pollution, outdoor air quality and ventilation rates have a strong impact on IAQ effect. In healing environments with low air spare parts and high relative humidity, the growth of fungi increases and it constitutes serious health risks (Settimo et al. 2017). In fact, high relative humidity and insufficient ventilation are the keys to the proliferation of toxic molds and the

M. Gola (✉) · S. Capolongo
Department of Architecture, Built Environment
and Construction Engineering, Politecnico di Milano,
Via G. Ponzio, 31, 20133 Milan, Italy
e-mail: marco.gola@polimi.it

S. Capolongo
e-mail: stefano.capolongo@polimi.it

A. Mele · B. Tolino
Politecnico di Milano, Piazza Leonardo da Vinci, 32,
20133 Milan, Italy
e-mail: ambramele@gmail.com

B. Tolino
e-mail: barbara.tolino@gmail.com

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dispersion of spores into the air, and it could also lead to an increased VOCs' release, especially in low levels of thermal insulation's buildings. This will affect IAQ and can cause a negative impact on occupant health due to exposure. In fact, it is well known that insufficient air changes and bad spaces' ergonomic and poor maintenance of ventilation systems have been identified as the main reasons for poor IAQ performance (Cristina et al. 2014).

In healthcare facilities, monitoring IAQ becomes an essential procedure for the hygiene and the control of airborne infections to ensure health and safety requirements for users, required to prevent and/or reduce the concentration of chemical, physical, and biological pollutants (D'Alessandro et al. 2016). These can determine nosocomial infections, which can be acquired by patients on admission, and some of them can acquire different ailments (Capolongo 2016). This can be caused by contact with a pathogen carrier, directly or indirectly through inanimate objects.

Currently, monitoring IAQ in architectures for health is not only faced by countries with a developed economy such as France, Portugal, and Greece, but also from developing countries such as China and Saudi Arabia. In Italy, instead, the indoor air monitoring is still not an in-depth issue, although there are several working groups that are working on.

There is a growing number of studies on IAQ assessment in healing environments regarding microbial contamination, while indoor chemical contamination in hospitals is rarely studied.

This paper presents a brief analysis of international case studies of IAQ analysis, assessment, and strategies. The selection of some specific international experiences is focused more on those concerning chemical indoor air pollutants, albeit presenting some on air biological contamination in healthcare settings and therefore the presence of biological agents, such as bacteria or fungi.

Hospital Pontchaillou, Rennes, France

Hospital Pontchaillou has a bed capacity of 1952. It was founded in 1679 and rebuilt in 1959. In addition to providing nursing service, it also hosts the training activities of the University of Rennes.

Monitoring Activity (Bessonneau et al. 2013)

The monitoring activity was conducted over three days in March 2012, by which compounds analyzed were defined by the administration of questionnaires to some representatives of the healthcare facility (Buffoli et al. 2014). The chemical pollutants, taken into consideration, concern five groups, such as laboratory products, products for the cleaning and disinfectant, alcohol-based products, pharmaceutical

and antiseptic products, and anesthetic gases. Some VOCs were selected due to the emissions' reduction of formaldehyde, acetaldehyde, tetrachlorethylene, BTEX (benzene, toluene, ethylbenzene, and xylene), styrene, and a few other consumer and building products in public buildings planned by European and French regulations. Others, including alcohols, terpenes, and ethers, instead, were included in the IAQ analysis due to specific activities carried out within the hospital.

The monitoring was carried out for evaluating the spatial and temporal variability of VOC concentrations in indoor air, taking air samples in six environments: reception hall, a regular patient room, nursing room, laboratory of parasitology mycology, unit post-anesthesia care unit (PACU), and flexible endoscope disinfection units.

Because outdoor air samples were not collected, the reception hall has been chosen as the control site, since the indoor air contamination is mainly due to sources related to non-health activities (Capolongo et al. 2016).

To evaluate temporal variations of chemical contamination, six sampling sessions were conducted: morning and afternoon during three days, using a low-flow pump, suitable for detecting the change of concentration over time (Ras et al. 2009).

The methods used in the activity of sampling for the qualitative analysis of air samples are two:

- first for the determination of aromatic and halogenated hydrocarbons, alcohols, ketones, and aldehydes (acrolein);
- second for aliphatic hydrocarbons, ethers, and terpenes.

Results (Bessonneau et al. 2013)

According to the surveys performed through the preliminary questionnaire to hospital staff, 58 different products used in the six sampling sites have been listed. The laboratory products are the most used (41%), followed by the cleaning and disinfectant ones (28%), pharmaceutical/antiseptics (19%), alcohol-based (7%), and anesthetic gas (5%) (Berrube et al. 2011).

In most of the different sampling sites, in order to reduce nosocomial infections, disinfectants and products for the cleaning based on alcohol have been used. The parasitology laboratory results to be the place with the largest number of products used, including the 73% strictly laboratory products (chemical products and reagents). A large number of products have also been used in hospital wards, with 11 pharmaceutical/antiseptics for patient care.

The results showed that the indoor air contamination is characterized by alcohols, particularly 2-ethylhexanol and ethanol. The concentrations of ether and acetone are relatively high compared to other compounds. For a large number of compounds, including some halogenated hydrocarbons, alcohols, ketones, and ethers, the standard deviation is greater than or equal to the arithmetic average, indicating a large variability of concentrations.

In all six sites considered in the monitoring activity, the concentration of aromatic hydrocarbons, in most cases, has not exceeded the prescribed values, with the exception of toluene. In addition, those with the highest values after toluene appear to be the m- and p-xylenes unit of disinfection. Values of benzene are different, with higher values in the laboratory of parasitology. However, significant concentrations are also recognized for ethylbenzene in unit of flexible endoscope disinfection, while the concentrations of trimethylbenzene, naphthalene, and phenol measured are approximately similar.

The rate of contaminant concentration is greater for chloroform. For trichloroethane, dichlorobenzene, and trichlorethylene, the highest concentrations were found in the unit of flexible endoscope disinfection, while the lowest were observed in the inpatient room and nursing one.

The concentrations of acetone are ubiquitous at similar sites in different levels, while the concentrations of butanone and cyclohexanone are widely variable between different sites. In fact, the butanone observed in the patient's room and in the laboratory of parasitology is higher than the concentrations found in other sites, and cyclohexanone of the six surveyed areas presented higher concentrations in nursing area.

Regarding the aldehydes, the results of the formaldehyde and acetaldehyde concentrations are equally distributed in all the sites. The highest concentrations were measured in the infirmary and in the inpatient room. Among the terpenes, it was only a measured limonene and more than half of the concentrations (66%) are less than the limit of quantification.

Finally, most of these compounds have been detected in the patient room, in nursing, and in PACU.

However, these compounds are also released from other sources that are not tied to specific hospital health activities, such as building materials or vehicular traffic. In order to differentiate the compounds coming from outdoor and those emitted within, the determination of the outdoor air VOC concentrations is required. This aspect represents a limitation of this study because external air samples were not collected.

However, the results have shown that indoor air at the sampling points contains a complex mixture of VOCs, and then, further multicenter studies are needed to compare these results. In any case, the benzene and formaldehyde concentrations measured do not exceed the guideline values established by French Decree No. 1727 (France 2011).

University Hospital of Democritus, Alexandroupolis, Greece

The university hospital was built in 2002 in Alexandroupolis (Greece). It has a maximum capacity of 671 beds and covers a total area of about 93.500 m^2.

Monitoring Activity (Gaidajis and Angelakoglou 2014)

The survey was carried out in two ICUs. The first one (ICU1), with an area of 30.8 m^2, a volume of 92.4 m^3, a windowed area of 15.1 m^2, and a capacity of 10 beds (during monitoring), is used for general medical accidents, while the second one (ICU2), with an area of 15.3 m^2, a volume of 45.9 m^3, a windowed area of 10.2 m^2, and a 6 bed capacity, focuses on patients undergoing cardiac surgery.

ICUs are isolated by positive pressurization, and staff varies from 3–4 doctors, 3–5 nurses, and 1–2 assistants for cleaning depending on the time and on their duties. During the morning hours, there are also groups of 8–10 students of medicine.

The monitoring activity aims to detect the concentration of particulate pollution. The sampling campaign was conducted for four days in May 2011 through two different monitoring devices both based on a light scattering technology to determine the concentration of the real-time mass, in order to ensure the completeness of the study (Gaidajis and Angelakoglou 2014).

Results (Gaidajis and Angelakoglou 2014)

The levels of the particulate concentration, in most cases, for both environments considered are satisfied slightly below the existing guidelines for PM_{10} and $PM_{2.5}$ (WHO 2006; Settimo and D'Alessandro 2014). However, maximum instantaneous concentrations of PM_{10} in ICU2 are significantly higher; furthermore, the average concentration levels of $PM_{2.5}$ are higher than the WHO guidelines.

The inconsistency of the results is due to the use of two different sampling instruments: In fact, the average of the device results in ICU1 is higher than ICU2 ones, arousing so many doubts in relation to an overestimation or underestimation of the values.

Regarding spatial variation of the surveys:

- In ICU1, concentration levels are higher than ICU2 ones. This can be attributed to the increased occupation of ICU1, since even in the absence of visitors in both ICUs, hospital staff, patients, and students in ICU1 further contribute to worsen the IAQ;
- It has been identified an association between the concentration of coarse particles and the number of visitors and patients, as it was found that in an ICU, the concentration levels of PM_{10} were higher after the patient's visit (Tang et al. 2009);
- The wider range of concentration emerged for PM_{10} in ICU1; and
- Concentration levels measured in ICU2 are evenly distributed, since the mean and median values tend to be equal.

The duration of the sampling of measured concentrations with the tool of ICU2 is less than ICU1, because of its inability to simultaneously measure PM_{10}, $PM_{2.5}$ and $PM_{1.0}$.

As it regards the temporal variation of surveys:

- Higher values for both ICUs were recorded during the morning shift, further supporting the idea that the trespassing can greatly influence the outcomes;
- Most of the measurements performed on ICU2 are above the indicative limits proposed by WHO;
- Cleaning activities seem to greatly affect the particulate concentration levels, probably because of the constant suspension of the latter (Dascalaki et al. 2009).

The cleaning activities are performed three times a day, and in these periods, it was possible to identify the maximum instantaneous values. It is well known that actions such as wet cleaning and an efficient ventilation during cleaning activities can have positive impacts in minimizing the negative effects of the increased indoor concentrations of particulate.

Hospitals di Guangzhou, China

The monitoring activity in Guangzhou, the richest city in southern China through trade and the presence of manufacturing industries, regards four hospitals.

Monitoring Activity (Lü et al. 2006)

The monitoring campaign of healthcare facilities in Guangzhou aims to detect carbonyl compounds and BTEX in the healing environments where most of the users stay, according to the method 14-A US EPA (US EPA 1999).

The carbonyl compounds are common components in the atmosphere, and they have received attention because of their potential negative effects on the health of human beings and their important role in atmospheric chemistry. Vehicle emissions and atmospheric photochemical reactions are considered the most impactful sources of carbonyl compounds in urban areas (Zhao et al. 2004). There are few studies in relation to hospital environments.

Hospital 1 (H1) is located in a suburban residential area, traffic congested, characterized by the presence of many factories in the surroundings. The sampling sites are considered to relate to the injection chamber, the hospital ward, and the outdoor conditions at the fourth floor (roof top). During the survey, the number of patients and visitors was about 15–30 people in the room injections and 20–45 people in all the departments.

Hospital 2 (H2) is located near a street of a high-density urban residential district, traffic congested. The surrounding area is characterized by the presence of restaurants, other businesses, and several buildings under construction. The sampling sites are considered to relate to the clinic, the type of ward, and the outdoor conditions at the tenth floor (roof). During the survey, the number of users was about 10–25 people in the clinic and 15–30 people in the department.

Hospital 3 (H3) is a children's hospital in an urban commercial district, located next to a pedestrian street. The sampling sites are considered to relate to the emergency room, the injection room, the department, and the outdoor air in the roof. During the analysis, patients and visitors were about 10–15 people in the emergency room, 20–30 in the room injections, and 25–40 in the department.

Hospital 4 (H4) is a tuberculosis hospital in an urban commercial district surrounded by Baiyun Mountain and Luhu Park. The sampling sites are considered to relate to the emergency room, the department, and the outdoor air at the roof level. During the survey, the number of patients and visitors was about 5–10 people in emergency room and 5–15 persons in all other departments.

Air samples in the four hospitals were collected in the first months of 2004.

Results (Lü et al. 2006)

The monitoring activities in the four hospitals have detected twenty-one kinds of carbonyls, among which acetone is most present, followed by acetaldehyde and formaldehyde.

The high concentrations of acetone in the environments were due in part to the outer level of acetone in Guangzhou to the presence of many factories in the surrounding areas and the growing increase of traffic in recent years. As emerged in H1 and H2, the concentrations of acetone and 2-butanone are obviously higher than outdoor, which may be due to paints and finishing materials (Gray et al. 2012). So both acetone and 2-butanone could be due mainly from the issuance of reagents used in industry, and accumulated in the air with specific weather conditions.

Moreover, the relatively high level of acetaldehyde concentration both inside and outside, even higher than that of most other data analysis, might be due to the wide use of ethanol as a disinfectant. The evaporating ethanol in the air reacts with OH and forms acetaldehyde.

Acetaldehyde is also a product of the human metabolism. Indeed, the presence of numerous patients in the injection rooms and then the direct emission from the human metabolism of acetaldehyde can be another reason for the high levels of concentration of this compound in H1 and H3.

In addition, correlations between propionaldehyde and butyraldehyde, and nonanaldehyde and decylaldehyde are all quite high. In Guangzhou, there are many flowers, grasses, and green plants all year-round thanks to the climate of the area, and there are also lots of trees and grasses in the vicinity of the sampling sites, so

the plant output can be another source of carbonyls, especially for some high molecular weights (Zou et al. 2003).

As regards the risk of BTEX, it was evaluated only the benzene. The results obtained from surveys show that all the air samples have not exceeded the limit of benzene. The toluene appears to be the most BTEX present in the case studies.

The correlations between the concentrations of benzene and other BTEX compounds appear to be generally adequate, suggesting that this may have common sources and that the most relevant ones are the vehicle emissions.

It is noted that in the case of Guangzhou hospitals, the concentration levels detected are considerably lower (a hundred times). This may depend upon the special use of a reagent on the sampling sites of previous studies or may also be due to the good ventilation of the sampling sites of hospitals, as objects of study (Lü et al. 2006).

University Hospital, Al-Khobar, Saudi Arabia

The university hospital in the city of Al-Khobar has more than 500 beds. The total number of employees includes 1.577 people (507 doctors, 481 nurses, 284 technicians, 244 hospital workers, 30 administrative employees, and 31 other workers). The hospital has three departments: medical, diagnostic, and administrative.

Monitoring Activity (El-Sharkawy and Noweir 2014)

The hospital analyzed the concentration levels of chemical indoor and outdoor air pollutants such as PM_{10}, CO, SO_2, NO_2, O_3, and VOCs, biological pollutants, temperature, and humidity relative values (Baxter et al. 2005). The monitoring campaign took into account main entrance, the burn unit, chemistry and biology laboratories, emergency room, ICU, the kitchen, the department of health center, surgery block, and pediatric units.

In addition, to detect the levels of outdoor air quality, three locations outside the hospital were selected near the door at a height of about 1.5 m.

The selected compounds were measured in 2 working days (Sunday and Tuesday), every week during the cold months (autumn and winter) and the warm ones (spring), in the academic year 2011–2012. The monitoring procedure was conducted in two different time periods, from 8 to 9 and from 10 to 11, every day. The first time period is the most significant period given that this constitutes the peak time and the activity of vehicular traffic within the building hospital, while the second time slot represents a relatively more quiet period of the day for the reduced vehicular traffic.

Simultaneously, chemical compounds responsible for indoor air pollution were detected by microbial air pollutants in operating rooms, in pediatric department and

emergency room, the unit of burns, ICUs (pediatric, medical, and surgical ones), and outdoor samples collected once a week to 8–10 h for measuring fungal spores.

The spore samples were collected with a sampler to occlusion at 1.2 m from the ground (the breathing zone), at the center of each department and with a flow rate of 100 L/min for a total duration of ten minutes.

Results (El-Sharkawy and Noweir 2014)

The outdoor levels of all air pollutants considered in the monitoring activity, except for VOCs, are much larger than the indoor concentration levels. This indicates that IAQ in hospital is greatly affected by the outdoor air, mainly by vehicular traffic.

However, the indoor levels of VOCs are higher than outdoors, as in health facilities, sources of these pollutants are identified in the chemical composition of disinfection and cleaning products.

Elevated concentrations of PM_{10} were found in healing environments characterized by an increase in human activities. Thus, the collected particulate levels, such as PM_{10}, $PM_{2.5,}$ and $PM_{1.0}$, turn out to be higher than the daily reference value, while the average concentration of sulfur dioxide was lower than the reference guidelines, but higher than the WHO ones.

The concentration levels of other considered compounds (CO, NO_2, $O_{3,}$ and VOCs) are lower than the values that ensure IAQ and the levels of indoor air guidelines. In particular, the levels of VOCs are in accordance with the hospital settings in which rapid treatments are provided, such as vaccination ones or where burns are treated with disinfectants, or where other cleaning products are used. For this reason, the highest levels of this pollutant were obtained in the emergency room, in the unit of burns, and in the pediatric ward.

In monitoring hospital activities, beyond chemical pollutants, also fungus models, MRSA (methicillin-resistant Staphylococcus aureus), and their concentrations were studied. With regard to the fungal spores, the emergency room presented the highest concentrations of different fungal species, especially Cladosporium and Penicillium. The same profile was detected in the outdoor environment, which showed that it has influenced the presence of fungi in indoor air. The results of the survey are to be in accordance with the study that identifies Cladosporium as the dominant genre (55%), while in the clinical units, Penicillium is the most fungal species present (23–25%) (Sautour et al. 2009).

The higher average concentrations of bacteria and fungi were found in the hall entrance, followed by the surgery department, ICU, and biomedical laboratory. The predominant bacterium in the air is Staphylococcus, with a percentage equal to 50%.

In addition, factors such as relative humidity, temperature, and occupants' density were analyzed in relation to the concentration of fungal spores and MRSA in the air. However, the frequent use of doors, the high respiratory activity by visitors and patients, and losses in the ventilation system in some old parts of the

hospital tend to increase the moisture and affect the number of airborne fungi (Tang 2009). According to the study, the results reported values of temperature and relative humidity for the growth of fungi, respectively, of 26 °C and 50–60%.

Assistência Psiquiátrica do Distrito de Viseu and Hospital de São Teotónio, Viseu, Portogallo

The psychiatric hospital was built in Viseu in 1969; it has a capacity of 210 beds, and it is naturally ventilated, without any cooling system. Differently, the hospital in São Teotónio was built in 1997; it occupies an area of approximately 15 hectares, with 632 beds.

Monitoring Activity (Monteiro da Silva et al. 2014)

The monitoring activity of these two healthcare facilities has detected the physical parameters responsible for thermal comfort and levels of concentration of some chemical pollutants (CO, CO_2, CH_2O, VOCs, O_3, PM_{10}, etc.) in different hospital environments daily. They were evaluated:

for the psychiatric center, several offices (general nurses, doctor, psychiatric ones, etc.), the library and archives, cafes, several lounges, meeting rooms, changing room, and corridors;
for the hospital, the areas of the psychiatric service, various corridors, type of ward, several offices, and meeting rooms.

For the survey of the parameters associated with thermal comfort and IAQ, they followed the procedures formulated by national and international standards (ANSI/ASHRAE 2010; Europe 2007; Portugal 2009, 2013).

Moreover, the monitoring campaign was supported by questionnaires, provided to occupants, based on the methodology defined in EN 15251: 2007, in order to even get a subjective evaluation of the thermal comfort and indoor air quality conditions (Buffoli et al. 2014). In the survey, the occupants were asked to answer questions related to thermal conditions and the temperature variation during the day, ventilation, IAQ, and global comfort conditions.

Results (Monteiro da Silva et al. 2014)

Thermal comfort conditions were not enough in the most of the environments, which is the aim of the study. In fact, the areas of the psychiatric facility by predicted mean vote (PMV) indicator are to be considered slightly cold and slightly

warm and hot, and the percentage of people dissatisfied (PPD) varies with values between 15 and 20% and above 60% in the waiting room and type of ward. Unlike in the healthcare facility of São Teotónio, the PPD varies with values between 15 and 20% and over 50% in the meeting room.

The results obtained during the monitoring activity showed the presence of high concentrations of some indoor pollutants, such as carbon dioxide and VOCs, thus resulting in a poor IAQ, due to the presence of a large number of individuals within the environments monitored during the sampling.

However, in all sites, there is a great concentration of CO_2 in the department, generally in offices and meeting rooms, but they do not exceed the reference guidelines (Portugal 2009, 2013).

In the psychiatric facility, the concentrations of VOCs and formaldehyde are generally 5 times higher than Portuguese limits imposed for 8 h (Portugal 2013). The detected VOCs greatly exceed the maximum reference value in different environments, while formaldehyde exceeds the Portuguese and WHO reference values only in waiting rooms. This is due to the presence of open containers for waste, antiseptics, and varnishes, in addition to the lack of adequate air changes that contributed to a remarkable concentration of several chemical pollutants responsible for an inadequate IAQ. Carbon monoxide and ozone have, however, not shown significant concentrations at or above the reference values.

In the case of Hospital de São Teotónio, instead, less relevant are the concentrations of carbon monoxide, which, with values ranging, appear to be well below the reference values. In all environments considered, ozone presents a concentration almost absent.

In addition, in the psychiatric structure, high airborne particulate daily concentrations have been identified in most of the hospital settings and the reference value at 24 h for PM_{10} is highly exceeded. In particular, the maximum concentration of PM_{10} was observed in the archives with values about 1000 times higher, while in the hospital, the airborne particulate concentrations in all the sites are compliant with the daily reference value by WHO.

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Hospital Environments and Epidemiology of Healthcare-Associated Infections

Daniela D'Alessandro and Gaetano Maria Fara

Introduction

Hospitals are confronted today with difficult challenges, represented by the increasing proportion of immunologically vulnerable patients often affected by diseases requiring high complex levels of healthcare (Capolongo et al. 2014); the rapidly evolving medical technologies and healthcare models; and the budget restrictions (Astley et al. 2015; Zantedeschi et al. 2003; Capolongo et al. 2016). All these features interfere with healthcare and can modify the risk of acquiring healthcare-associated infections (HCAIs). Therefore, HCAI prevention is a high priority for all healthcare systems (WHO 2011).

Many studies show that hospital built environment influences the risk of acquiring HCAIs (Sehulster and Chinn 2003; Capolongo 2016), although, at present, its quantitative impact is not yet known (WHO 2011); some studies show that a careful consideration of environmental transmission routes in the design and operation of healthcare facilities can significantly reduce the burden of HCAIs (Sehulster and Chinn 2003; Seigel et al. 2007; D'Alessandro and Capolongo 2009; Bartley and Streifel 2010).

Several environmental HCAI agents do not usually involve person-to-person transmission. For example, spores of environmental fungi and bacteria (e.g., *Aspergillus* spp. and *Legionella* spp.) may cause disease, mainly in immunocompromised subjects, who inhale aerosolized microorganisms coming from con-

D. D'Alessandro (✉)
Department of Civil Building Environmental Engineering, Sapienza Università di Roma, Via Eudossiana, 18, 00187 Rome, Italy
e-mail: daniela.dalessandro@uniroma1.it

G.M. Fara
Department of Public Health and Infectious Diseases, Sapienza Università di Roma, Piazzale Aldo Moro, 5, 00185 Rome, Italy
e-mail: gaetanomaria.fara@uniroma1.it

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struction dust, or moisture and dust accumulated within heating, ventilation, and air-conditioning (HVAC) systems, or water aerosolized from distribution systems, etc. (Seigel et al. 2007; Kumari et al. 1998; D'Alessandro et al. 2015).

Several factors make hospitals suitable for microbial environmental colonization, increasing the HCAI risk; for example,

1. the abuse of antimicrobials induces the formation of a large reservoir of resistant microbial strains (WHO 2011);
2. the infrastructure repairs and the renovation of aging hospitals cause the release of dust-containing fungal spores during construction and, in particular, demolition activities (D'Alessandro and Capolongo 2009; Baglioni and Capolongo 2002);
3. the simultaneous presence and interaction of different types of subjects, such as patients, healthcare workers, and visitors, often in the absence of behavioral rules;
4. the lack of financial support for maintenance and adequate sanitization (WHO 2011);
5. the inadequate training of personnel in the field of HCAI control (D'Alessandro et al. 2014).

This paper examines in particular how HCAI agents spread among hospitalized patients via environmental routes, focusing on the mechanisms of airborne transmission and the ways the design, construction, renovation, and maintenance of the hospital play a critical role in preventing—or favoring—the environmental contamination and the spread of infections.

Microorganisms in Hospital Indoor Environments: Where Do They Come from?

Airborne pathogens, involved in HCAIs, may have (a) a human or (b) environmental origin. Therefore, they can enter the air by a variety of routes.

Most airborne microorganisms within the building are of ***human origin***: staff, patients, and visitors. Generally, the higher the bed occupancy level, the greater the microbial bioburden in the air (Beggs 2003). Humans spread infectious particles of respiratory secretions by coughing, sneezing, or talking. On average, a cough can generate some 3,000 droplet nuclei, and the same can do speaking for 5 min; sneeze can generate as many as 40,000 droplet nuclei. Droplet nuclei are large particles that settle out from the air, but once evaporated into particles in the 0.5–12 μm range (Cole and Cook 1998), they can be resuspended in the indoor air. Other aerosol-generating activities are represented by making a bed: In that case, skin scales shed by patients infected with methicillin-resistant Staphylococcus aureus represent a reservoir for airborne infections (Ulrich et al. 2008).

As far as the ***environmental origin*** of airborne pathogens, a problem until now underestimated is the "microbial ecology" of hospital building. Actually, their potential effects on human health can be minimized through proper design, construction, operation, maintenance, and cleaning. In particular, the extent and persistence of moisture in various structural, finishing, and furnishing materials is a problem of greatest importance (Cole and Cook 1998; D'Alessandro and Capolongo 2009). If relative humidity is uncontrolled or if leaks, floods, or sewage backups are not readily and properly repaired, the result is an altered microbial ecology that permits the amplification (overgrowth) and dissemination of fungal and bacterial species with the potential for opportunistic nosocomial infections (Cole and Cook 1998; Vonberg and Gastmeier 2006). Microorganisms grow in moisture films on several surfaces and within porous materials. The amount of free water available to them for growth on a substrate or microenvironment (e.g., ceiling tile) is described as *water activity* (a_w), the ratio of the vapor pressure of water in the substrate to the vapor pressure of free water. Increased a_w due to high relative humidity, leaks, or floods, if allowed to persist more than 24 h, changes the normal ecology of a microenvironment or of the entire building, with microbial competition resulting in the predominance of one or more organisms with potentially damaging effects upon materials and health. Fungi require the lowest a_w level to grow. Most fungi have a minimum requirement of a_w of at least 0.88%, but some fungi have even lower limits, down to 0.66–0.70% (Cole and Cook 1998; D'Alessandro et al. 2016).

Other, more occasional cases or outbreaks of environmental airborne HCAI are due to exhaust ducting of the ventilation systems, cooling towers, aerosol produced by faucets, shower heads, humidifiers, nebulizers, etc. (Sehulster and Chinn 2003; Kumari et al. 1998; D'Alessandro et al. 2015). Furthermore, outdoor and indoor construction, ceiling tile, and contaminated carpets have been involved in outbreaks due to fungal spores (D'Alessandro and Capolongo 2009; Sehulster and Chinn 2003).

How Can Microorganisms Be Transmitted Through the Air?

Establishing how microorganisms are transmitted under different circumstances, and whether transmission requires close contact, is of great importance as such information affects the choice of infection control measures in healthcare settings.

The main routes of HCAI transmission are contact, droplet, and airborne.

Contact modality includes all the infections where the victim is in *direct* (person-to-person) or *indirect* (person–inanimate object–person) contact with the source of infection (Beggs 2003; Seigel et al. 2007).

Droplet transmission is, technically speaking, a kind of contact transmission, and some infectious agents transmitted by the droplet route are the same which are

transmitted by the direct contact route (Seigel et al. 2007). However, in contrast with the traditional contact transmission, respiratory droplets carrying infectious pathogens transmit infection when they travel directly from the respiratory tract of the infectious individual to susceptible mucosal surfaces of the recipient, generally over short distances. Respiratory droplets are generated when an infected person coughs, sneezes, or talks or during procedures such as suctioning, endotracheal intubation, cough induction by chest physiotherapy, and cardiopulmonary resuscitation (Seigel et al. 2007).

The maximum distance for droplet transmission is an unresolved issue, even if the pathogens transmitted by droplet route have not been transmitted through the air over long distances (Sehulster and Chinn 2003, Seigel et al. 2007; Jones and Brosseau 2015). The literature suggested that area of defined risk has been a distance of <3 feet around the patient (Sehulster and Chinn 2003; Seigel et al. 2007; Jones and Brosseau 2015), although other studies on smallpox (Fenner et al. 1988) and SARS (Wong et al. 2004) indicate that droplets from patients could reach persons located 6 feet or more from their source, depending on the velocity and mechanism by which respiratory droplets are propelled from the source, the density of respiratory secretions, environmental factors such as temperature and humidity, and the ability of the pathogen to maintain infectivity over that distance (Cole and Cook 1998).

Droplet size is another variable under discussion (Seigel et al. 2007; Jones and Brosseau 2015). Droplets traditionally have been defined as being >5 μm in size. *Droplet nuclei*, particles arising from drying of suspended droplets, have been associated with airborne transmission and defined as ≤5 μm in size (Seigel et al. 2007). These values arose from a study (Wells 1955) regarding pulmonary tuberculosis transmission, which is not exactly applicable to other organisms; at that time, sampling methods were unable to measure particles suspended in air around the infectious source. Observations of particle dynamics have demonstrated that a range of droplet sizes, including those with diameters of 30 μm or greater, can remain suspended in the air (Cole and Cook 1998). In general, whereas fine airborne particles containing pathogens that are able to remain infective may transmit infections over long distances, organisms transmitted by the droplet route do not remain infective over long distances and therefore do not require special air handling and ventilation (Seigel et al. 2007).

Airborne transmission (AT) is a type of indirect contact, and it refers to infections which are contracted from microorganisms which have become airborne, namely particles that are transported by convective air currents (Beggs 2003). AT generally applies to microorganisms contained in droplet nuclei produced by coughing, sneezing, or some other form of aerosolization, but it also applies to dust particles of environmental origin or skin scales, carrying pathogenic microorganisms and fungal spores, also widely disseminated via the airborne route (Beggs 2003). Overall, this route of transmission accounts for 10–20% of endemic HCAIs (Beggs 2003). Microorganisms carried in this manner may be dispersed over long distances by air currents and may be inhaled by susceptible individuals who have not had face-to-face contact with (or been in the same room with) the infectious

individual (Seigel et al. 2007). The prevention of the spread of airborne transmitted pathogens (e.g., *Mycobacterium tuberculosis*, measles (rubeola) virus, and varicella zoster virus) requires the use of special air-handling and ventilation systems to contain and then safely remove the infectious agent and also a specific respiratory protection.

After the emergence of SARS in 2002 and other subsequent outbreaks (e.g., avian influenza), the literature showed conflicting information about possible route of transmission. For certain respiratory infectious agents (e.g., influenza and rhinovirus and SARS-CoV) and some gastrointestinal viruses (e.g., norovirus and rotavirus), the pathogen may be transmitted via *small-particle aerosols*, in addition to the primary droplet and contact routes. In the case of gastrointestinal viral infections, it is hypothesized that the aerosolized particles from vomitus or fecal material are inhaled and subsequently swallowed (Seigel et al. 2007). Such transmission has occurred over distances longer than 3 feet but within a defined airspace (e.g., patient room), suggesting that it is unlikely that these agents remain viable on air currents that travel long distances. Small-particle aerosol, however, is not defined relative to the three conventional transmission routes (Cole and Cook 1998).

Therefore, a new classification for aerosol transmission was proposed by Roy and Milton (2004) to evaluate the routes of SARS transmission. It includes the following:

1. Obligate: Under natural conditions, disease occurs following transmission of the agent only through inhalation of small-particle aerosols (e.g., tuberculosis);
2. Preferential: Natural infection results from transmission through multiple routes, but small-particle aerosols are the predominant route (e.g., measles and varicella); and
3. Opportunistic: Agents that naturally cause disease through other routes, but under special circumstances may be transmitted via fine particle aerosols.

This conceptual framework can explain rare occurrences of airborne transmission of agents that are transmitted most frequently by other routes (e.g., smallpox, SARS, influenza, and noroviruses). Concerns about unknown routes of transmission of agents associated with severe disease often result in more extreme prevention strategies than may be necessary; therefore, recommended precautions could change as the epidemiology of an emerging infection is defined and controversial issues are resolved.

Recently, after the 2013 Ebola Virus Disease (EVD) outbreak, other authors introduced the concept of **aerosol transmission** (Jones and Brosseau 2015) to better define the route for small-particle aerosol and to move from the artificially dichotomized airborne and droplet transmission routes toward a more physically appropriate representation of the exposure and infection process. An aerosol is a collection of solid or liquid particles suspended in a gas, such as air, that may contain particles of any size. The fate of an aerosol in the environment is governed by physical processes (gravitational force, air movement, etc.). In the context of

infectious disease transmission, many processes and procedures generate aerosols that may contain both body fluid particles and pathogens. Infectious aerosols are subject to the same transport processes of other aerosols. The range of particle sizes included depends on several factors such as the mechanism of aerosol generation, the viscosity of the aerosolized fluid, and its liquid content. The liquid content influences the extent to which the particle size reduces with evaporation. From the authors' perspective, the concept of aerosol transmission is of primary importance to occupational health and it should trigger consideration for controls, such as respiratory protection, that limit workers' exposures when in the proximity of infectious patients, regardless of evidence for airborne transmission (Jones and Brosseau 2015).

The assessment of airborne infectious entities requires investigation not only into their generation, their particle sizes, and their aerodynamic properties, but also into their concentrations, their infectivity and virulence, and their viability with respect to climate factors (temperature and relative humidity) (Cole and Cook 1998).

Obviously, the survival of bioaerosols is a key factor and depends on their suspending medium, temperature, relative humidity, oxygen sensitivity, and exposure to UV or electromagnetic radiations. Once aerosolized in the indoor environment, microorganisms are subject to lethal desiccation, which results from an interplay of organism morphology, physiology, oxygen sensitivity, and suspending medium, with varying levels of relative humidity and temperature, in addition to air movements, pressure fluctuations, air ions, and other airborne pollutants (Cole and Cook 1998). Thus, the survival potential of any given microbial pathogen when aerosolized is unique to that organism under those specific conditions at that particular point in time.

The variability of impact of climatic conditions on the survival of different microorganisms makes the role of the environment extremely complex, and the knowledge in this field needs to be further developed.

Infective Doses and Implication for Building Ventilation

As known, the infectious disease depends on the microorganism concentration (infective dose) and its virulence that enable the agent to overcome the normal defenses of the host. Some microbial diseases require only small infective doses because the agents have affinity for specific tissue and possess one or more potent virulence factors that make them resistant to inactivation (e.g., *F. tularensis*, *M. tuberculosis, measles,* and *influenza viruses*) (Cole and Cook 1998).

Since the number of microorganisms required is frequently unknown, to model the transmission of respiratory pathogens, such as TB or measles, that spread more easily in a crowd rather than by close contact, Wells–Riley in late 1970s (Riley et al. 1978) proposed an equation and used the term "quanta" (q) as "*the number of infectious airborne particles required to infect which may be one or more airborne particles*." The Wells–Riley equation has several important limitations: it assumes

that the air in the space is fully mixed and does not account for heterogeneity in infectiousness or susceptibility to infection (Yates et al. 2016). Subsequently, adaptations of the equation have been published. One popular variant uses a rebreathed fraction, the fraction of inhaled air that has been exhaled previously by someone in the building (Nardell 2016). This rebreathed fraction can be obtained from paired indoor and outdoor carbon dioxide measurements. This process avoids the need to measure Q, which can be technically challenging. It is an indirect way to evaluate the exposure level.

However, patients vary greatly in infectiousness. For example, for tuberculosis, this variability is related to the characteristics of the source patient (e.g., frequency of cough, viscosity of respiratory secretions, and presence of lung cavities or laryngeal disease), the strain virulence, the vulnerability of exposed hosts, and environmental factors, but they are difficult to separate. The same source patient and strain will infect more contacts in a crowded, poorly ventilated environment with highly susceptible hosts (Nardell 2016).

Building occupancy correlates with risk for at least two synergistic reasons: the greater the number of those present in the room (or building), rebreathing each others' air, the greater the risk of presence of an infectious source or sources in that population and the greater the number of exposed occupants (Nardell 2016).

Airborne fungi, most notably *A. fumigatus* and other species, pose an extremely serious infectious disease threat to those who are immunocompromised as a result of immunosuppressive or cytotoxic therapy (D'Alessandro and Capolongo 2009). Hospital outbreaks of pulmonary aspergillosis have occurred mainly among patients with granulocytopenia, especially in bone marrow-transplant units. For these high risk patients, it has been estimated that even concentrations of *Aspergillus* spp below 1 colony-forming unit/m^3 were sufficient to cause infection (Vonberg and Gastmeier 2006).

Control of Airborne Transmission of Pathogens

In order to apply the appropriate control measures and to avoid unnecessary costs, to control airborne transmission of pathogens, it is necessary to identify the areas where the risk of airborne infection is the greatest. This can be done through a process called *infection control risk assessment* (ICRA) and its subsequent revisions (FGI 2014); it is a multidisciplinary, organizational, documented proactive process designed to enable the organizations to anticipate the potential impact (D'Alessandro and Capolongo 2009). In summary, ICRA identifies groups of patients at risk and areas where infection control is necessary in order to define the appropriate measures for infection control and maintenance programs.

In particular, the hospital patients interested by the risks associated with airborne infection can be divided into two groups: (a) *infectious patients*, who may spread infectious agents such as tuberculosis, varicella, and rubella, and (b) *susceptible patients* (e.g., bone marrow- and solid organ-transplant recipients, those undergoing

cancer treatment, babies born prematurely, AIDS patients, and patients whose immunity is compromised by interventions such as surgery), who are vulnerable to such agents but also to common opportunistic infectious agents.

The areas in which airborne infection control is necessary include (a) *airborne infection isolation rooms*, where airborne infectious agents could be contained (e.g., convalescence rooms, emergency rooms, examination rooms, intensive care units, radiology and diagnostic rooms, and procedure rooms), and (b) *protective environments*, such as operating and bone marrow-transplant rooms, which must be free of airborne infectious agents.

Pressure control via an offset between supply and exhaust air volumes is essential to prevent the migration of unwanted airborne contaminants into critical areas. Over supplying a protective environment, it provides an airflow from clean to less clean direction.

Isolating a patient in a room with controlled airflow is another strategy to prevent the airborne spread of infection. The 2003 CDC guidelines address controlling airflow from unclean to clean through the use of pressurization and anterooms (Sehulster and Chinn 2003). Positive pressure rooms prevent the outside air from getting into the room and are useful for keeping potentially contaminated air away from immunocompromised patients, including those with neutropenia following chemotherapy.

Patients with highly transmittable airborne pathogens should be placed, on the contrary, in a negative pressure isolation room, which can prevent the transmission of pathogens such as *Mycobacterium tuberculosis,* varicella (chicken pox), and rubeola (measles) (Sehulster and Chinn 2003). These negative pressure isolation rooms are typically single-patient rooms.

Positive pressure ventilation is used to protect the vulnerable patients. While the needed number of rooms with special ventilation depends to some degree on the patient population served by the hospital, single-patient rooms with negative pressure ventilation should be added to all existing and new constructions (Bartley and Streifel 2010).

Actually, single-patient rooms and flexible acuity rooms are the trend in hospital planning and design (Bartley and Streifel 2010). In addition to the reduction in the risk of cross-infection, the reported advantages of single-occupancy rooms included also improvements in patient care and greater flexibility in operation. However, it is important to view and interpret the benefits of single rooms within the context of patient care issues, other environmental changes, and management policy changes to bring about desired and sustainable outcomes.

Other suggested measures to interrupt the airborne transmission of pathogens (Jacob et al. 2013) include the control of the flow and quality of air to minimize the exposure to airborne pathogens and the use of filters to trap particles, including pathogens, and to remove them from circulation.

Specific indications on most of indoor air quality requirements are reported in the 2003 CDC guidelines (Sehulster and Chinn 2003). HVAC systems are the primary mechanism for controlling air in the hospital environment; their goals are to replace potentially contaminated air with clean air, to minimize the mixing of dirty

and clean air, and to regulate ambient temperature and humidity. In addition, filtration of ventilated air can reduce the number of airborne pathogens. Air filters are rated based on the size of particles they are able to remove, and high-efficiency particulate air (HEPA) filters are widely used in healthcare settings, having an efficiency of at least 99.97% at a test aerosol diameter of 0.3 μm (Sehulster and Chinn 2003). HEPA filters remove airborne pathogens in critical areas such as operating rooms, transplant units, isolation rooms, and intensive care units. Filtration is a strategy that utilizes several levels of filters, the highest of which is HEPA filter. The use of HEPA filters is widespread in hospitals, especially in areas that house immunocompromised patients. Another issue related to HVAC systems is the appropriate type of airflow direction to recommend for protective environment. Multiple technologies are currently available to control the direction of airflow inside the hospital, although no consensus exists whether turbulent, displacement, or unidirectional airflow is the most effective (Jacob et al. 2013). Traditional ventilation systems in patient care areas utilize turbulent air to direct airflow rapidly away from patients. also called *unidirectional airflow*), used most commonly in operating room, is a method of air ventilation in which ultraclean air that has passed through a HEPA filter is distributed either vertically or horizontally in a smooth stream directed over the patient. Although unidirectional airflows seem to be the gold standard, the evidence supporting their use in operating rooms and other protective environments is not enough, because their impact on infection rates remains unresolved (Jacob et al. 2013; Agodi et al. 2015); therefore, further investigations are required.

Effective Air Quality Control Measures During Construction and Renovation

Finally, it is extremely important to employ effective control and prevention measures during construction and renovation, because such activities have been frequently implicated in outbreaks of airborne infection. The ICRA approach, described above, can help to classify the risk level of each yard and to define the appropriate control measures for air quality (D'Alessandro and Capolongo 2009). Examples of such measures include using portable HEPA filters, installing barriers between patient care areas and construction/renovation areas, generating negative air pressure for construction/renovation areas relative to patient care areas, and sealing patients' room windows (D'Alessandro and Capolongo 2009; Ulrich et al. 2008). The application of accurate cleaning protocols to reduce environmental dust is also required (D'Alessandro and Capolongo 2009).

Conclusions

After the outbreaks of SARS in 2002–2003, the concerns about an expected avian influenza (H5N1) pandemic and the recent outbreak of Ebola virus disease, the airborne infections have attracted more attention, following a long period in which their role may have been underestimated, due to the difficulty of culturing many airborne organisms and the complexities of assessing the role played by such pathogens in the contamination of environmental surfaces and subsequent contact transmission (Ulrich et al. 2008; Beggs 2003).

Although spread by contact is an important and well-known environmental mechanism of infections, this paper has been intentionally focused on HCAI of airborne origin. Therefore, some design aspects of interest in the prevention of HCAI (e.g., handwashing station design and placement, surfaces and furnishing features) have not been described.

Despite these intentional choices, some conclusions can be of general interest. One is that in order to prevent HCAIs, two kinds of expertise are necessary, namely knowledge of traditional infection control and knowledge of human behaviors, to help healthcare workers employ infection control science effectively (Hamilton and Stichler 2013). Actually, the effectiveness of preventive measures is related to the availability of appropriate periodic maintenance programs to assure the safe ventilation of indoor air, but also the strict compliance with the procedures by the staff (D'Alessandro et al. 2014; Agodi et al. 2015).

Therefore, it is of paramount importance to increase the healthcare workers' awareness of the risks associated with incorrect behaviors and to improve their training, because, independently from the technology available, the human behavior is crucial to ensure the indoor air quality and safety in healthcare setting (Pitzurra et al. 1997; D'Alessandro et al. 2014; Agodi et al. 2015).

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Analysis of Microorganisms in Hospital Environments and Potential Risks

Lucia Bonadonna, Rossella Briancesco, and Anna Maria Coccia

Introduction

The term hospital environment includes hospital buildings and healthcare settings with all indoor components that differentiate them: occupying people (sick people, visitors and hospital staff), indoor air, surfaces, medical equipment, drugs, medical devices, food and wastes (Bottero et al. 2015; Capolongo et al. 2016).

All these components may potentially support survival and growth of biological agents. How microbial communities persist and change in indoor environments is of great concern to public health. In fact, recent studies demonstrated that when humans occupy a space, human being there alters the microbiota of that space (Smith et al. 2013; Capolongo et al. 2015b).

Within hospitals, people can be exposed to bioaerosols, particles of biological origin suspended in the air, and the potential for contracting a microbial pathogen is high. The human exposure to pathogens may be associated with a wide range of major public health issues, such as infectious diseases, acute toxic effects and allergies.

Hospital environments are characterized by high infective risk, firstly cause of the compromised immunologic conditions of the patients that make them vulnerable to bacterial, viral, parasitological and fungal opportunistic infections (D'Alessandro et al. 2016). The potential transmission of biological matter during surgery operations and medical treatments of infected individuals makes hospital

L. Bonadonna (✉) · R. Briancesco · A.M. Coccia
Department of Environment and Health, Istituto Superiore di Sanità,
Viale Regina Elena 299, 00161 Rome, Italy
e-mail: lucia.bonadonna@iss.it

R. Briancesco
e-mail: rossella.briancesco@iss.it

A.M. Coccia
e-mail: annamariacoccia@iss.it

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environments strongly designated to become easily contaminated with spread of pathogens among patients (Baglioni and Capolongo 2002).

Furthermore, in the last decades, if the use of antibiotics has been an excellent tool into preventing nosocomial infections, the extensive employ of these drugs has inevitably conducted to the insurgence of antibiotic resistance events.

Hospital buildings may be considered as dynamic environments affected by several factors that actively contribute to define the infective risk for patients. Aspects that have to be considered are represented by the number of occupants (in addition to patients, medical employees and visitors), their effective state of health, hygienic habits and activity occurring at any time in the hospital (Capolongo et al. 2015a; Astley et al. 2015). Hygienic conditions of sites and rooms, building materials and equipment, furnishings also influence the microbial community composition (Signorelli et al. 2016). In addition, technological devices such as hydraulic, heating and air-conditioning systems may represent a potential source of bacteria, fungi (moulds), virus and other organisms if not adequately designed and submitted to a planned preventive maintenance.

Microclimatic conditions and accidental events can support microbial and fungal growth (water infiltration and condensation) causing harmful indoor conditions (Buffoli et al. 2007). Outdoor microbial load and seasonal climatic characteristics also affect the microbiological quality of the hospital indoor air.

Sources of Hospital-Acquired Infections and Routes of Transmission

Hospital-acquired infections are emerging as important cause of morbidity and mortality in immunocompromised patients and severe underlying illnesses. Each year, 2 million patients suffer from hospital-acquired infections and nearly 100,000 of them die (Klevens et al. 2007). Data from the World Health Organization show that on 100 hospitalized patients, 7–10 are expected to contract, at least, one healthcare-associated infection (WHO 2011). However, the real burden is unknown because of the difficulty to gather reliable data. In fact, the diagnosis of nosocomial infections is complex and based on multiple criteria and not on a single laboratory test.

In healthcare facilities, the main sources of infection are the patients and the healthcare employees, although the environment plays also an important role. In fact, environment may act as a reservoir for potential infective microorganisms and may contribute to their dissemination. Consequently, bacteria are also common on inanimate surfaces, equipment and indoor air.

Infected patients spread microorganisms in the hospital sites through the release of expectorate drops, fluids from infected wounds, excrements, urine, blood, other corporeal fluids, but also through clothes and blankets. In addition to pathogenic microorganisms, the patients' endogenous flora could be a consistent source of microbes.

Microbial spread occurs mostly via large droplets, direct contact with infectious material or through contact with inanimate objects contaminated by infectious material. The direct contact between patients is rare; hands of clinical personnel can spread infective microorganisms and represent the most frequent vehicle of nosocomial infections. Thus, hand hygiene is recognized as the primary measure to reduce infections.

Even healthy people and staff may act as carriers when infected or colonized. Pathogens such as *Staphylococcus aureus, Staphylococcus pyogenes, Neisseria meningitidis, Corynebacterium diphtheriae,* hepatitis B virus, cytomegalovirus can be transmitted by symptomless carriers.

Pathogens and opportunistic pathogens may be present in water distribution systems and in aerosol released by water-cooling systems (e.g. *Legionella* sp., *Mycobacterium* sp.). Microbial contamination can also occur in pharmaceuticals during the distribution among patients and in improperly processed food. In addition, hospital wastes not rightly and quickly eliminated can become a harmful contamination source.

Microorganisms that can be spread by contact include those associated with impetigo, abscess, diarrhoeal diseases, scabies and antibiotic-resistant organisms (methicillin-resistant *Staphylococcus aureus* and vancomycin-resistant enterococci). Vectorborne transmission is limited to areas in which insects, arthropods and parasites are widespread.

Water and aqueous solutions used in healthcare facilities are often associated with the hospital-acquired infections. Despite water treatment and chlorination, water entering in the hospital distribution systems may contain low concentrations of various autochthonous microorganisms such as *Pseudomonas* sp., *Legionella* sp., nontuberculous mycobacteria, *Acinetobacter* sp., *Aeromonas* sp., *Sphingomonas* sp., *Enterobacter* sp., *Aspergillus* sp. and amoebae, which may cause clinically important opportunistic infections. Remaining embedded in a matrix of extracellular organic polymers combined with nonorganic particles, these microorganisms can induce the development of biofilms in the plumbing system of healthcare facilities, hot water tanks, air-conditioning cooling towers, sinks, shower heads and faucet aerators. In addition to own each group characteristics, the biofilm constitutes a barrier, thus preventing both the complete cleaning of the environment that the total elimination of the microorganisms, with the consequent presence of survivors that, in the same time, can develop resistance to biocides and transmit this resistance, whether genetic, even in microorganisms of other species.

Some biofilm-forming bacteria such as *Legionella, Klebsiella, Pantoea agglomerans, Acinetobacter baumannii* and *Enterobacter cloacae* can cause hospital infections and are more resistant to disinfectants and antibiotics than their planktonic states. Biofilm can act as microbial reservoir that constantly releases viable microbes into the water stream. Tap water may then contaminate surfaces, medical devices and instruments as well as endoscopes, dialysis machines, nebulizers, humidifiers and ventilators (Exner et al. 2005).

The routes of transmission of waterborne pathogens include direct contact, ingestion of water, indirect contact and inhalation of bioaerosols. *Pseudomonas*

aeruginosa and *Legionella pneumophila* are the most significant waterborne pathogens in healthcare facilities.

P. aeruginosa is an environmental common microorganism. It is frequently associated with nosocomial infections, particularly among mechanically ventilated or immunocompromised patients in intensive care units. The major reservoir of *P. aeruginosa* is considered the patients' endogenous flora, and horizontal transmissions among patients have long been considered the most frequent source of *P. aeruginosa* infections. Other studies have shown patient-to-patient spread via hands of healthcare workers, or via fomites.

However, during the last years, the application of molecular typing methods made it possible to identify tap water supplied by intensive care units as a significant source of exogenous *P. aeruginosa* isolates. A review of prospective studies showed that between 14.2 and 50% of infection/colonization episodes in patients were due to genotypes found in intensive care unit water (Trautmann et al. 2005).

L. pneumophila has been recognized as the first emerging waterborne pathogen transmitted by inhalation. Its transmission represents a considerable risk for patients with chronic lung disease and those who undergo general anaesthesia. In hospitals, the immunosuppressive status of patients and other risk factors induce not only a higher risk of infection but also a higher incidence of lethality than in other settings. From 5 to 20% of notified legionellosis are of healthcare-associated origin (Exner et al. 2005). In healthcare settings, not only humidifiers, respiratory devices and cooling towers, but also showers and taps are specific reservoirs of *Legionella* (Joly and Alary 1994; WHO 2007; ANSI/ASHRAE 2015).

Nontuberculous mycobacteria (NTM), even called environmental mycobacteria, are also responsible for healthcare-associated infection by inhalation route and direct contact. The structure of their cellular wall particularly rich of long-chain lipids and the ability to form biofilms contribute to their resistance to chemicals and support their persistence. Indeed, NTM are frequently found in water distribution systems and can be aerosolized through showers and taps. A microbiological survey carried out by the authors confirmed NTM presence in the water plumbing of a hospital after the occurrence of some cases of atypical mycobacteriosis in a hospital wards. The NTM load ranged between 2×10^2 and 4×10^4 cfu/L and human pathogenic opportunistic NMT species (*M. intracellulare, M. chelonae, M. llatzerense and M. gordonae*) were found in addiction to other harmless environmental species (Briancesco et al. 2014).

Since the risk resulting from the presence of NTM in water is not controllable by classical water disinfection procedures, filters at the point-of-use are now recommended to be the best option for minimizing the risk.

Moreover, water distribution systems may be potential indoor reservoirs of moulds such as *Aspergillus* sp., zygomycetes, *Fusarium* sp. and other fungi. Showers and taps can be the sources of risk for aerosolization of fungal spores (Anaissie et al. 2003). Moulds are ubiquitous in nature and grow almost anywhere indoors or outdoors. Persons can be exposed to mould through skin contact, inhalation or ingestion. Because of the ubiquity of mould in the environment, some level of exposure is inevitable. Inhalation is usually presumed to be the most

important mechanism of exposure to viable (live) or nonviable (dead) fungi, fungal fragments or components. The majority of fungal spores have aerodynamic diameters of 2–10 μm, which are in the size range that allow particles to be deposited in the upper and lower respiratory tract. Inhalation exposure to a fungal spore requires that the spore be initially aerosolized at the site of growth. In general, persons with impaired host defences suffer the most severe types of fungal infections.

Spread of Airborne Microorganisms

Airborne hospital microorganisms are apparently harmless to healthy people. Nevertheless, they can cause adverse health effects in immunocompromised individuals.

The hospital itself and its technological systems can offer detrimental sources to the indoor air quality. Air-conditioning systems and aeraulic plants can become contaminated over time and trap various contaminants such as dust and biological organisms. Moisture from them can condense within the ducts and support microbial growth. Thus in hospitals, special air handling and ventilation are required to prevent airborne transmission (ANSI/ASHRAE 2016). Inadequate ventilation is implicated in the airborne transmission of bacteria (Obbard and Fang 2003).

Bioaerosol spread through the air cover in a wide size range. Droplets are larger than 5 μm and their source is primarily the act of coughing, sneezing or talking. In hospitals, particular medical performances such as suctioning and bronchoscopy spread particles of this size. Among droplet-transmitted infections, smallpox, measles, chickenpox, tuberculosis, meningococcal disease, pneumonia caused by *mycoplasma*, SARS and flu are the most relevant.

Small particles residual from evaporated droplets (5 μm or smaller in size) and dust particles containing infectious agents may remain suspended in air for a long time. In this way, microorganisms can be dispersed widely by air currents over a longer distance from the source. The airborne transmission of infections regards only microorganisms spread in large number into the air with low infective dose. Key factors influencing the level of airborne microbial burden are the occupant density and dampness depending on the particular location within the hospital.

In hospital indoor air quality moulds are frequently recovered, especially during the construction/repair activities. Fungal spores have low settling velocities remaining in the air for a long time.

The hospitalized weakened patients are more susceptible to infections from naturally occurring mesophilic fungi, and in last decades, high mortality rates have been reported in transplant patients and leukaemia patients (Taccone et al. 2015).

In a survey study that followed the occurrence of numerous post-surgery infections at a transplant centre of a hospital in Rome, the levels of bacteria and fungi occurring in air and surface samples from an operating block (operating rooms, intensive care units, surgery recovery rooms and annexes corridors) were assessed.

Low concentrations of fungi were found in air and surface samples (ranging from 0 to 70 cfu/m^3 and from 0 to 21 cfu/cm^2, respectively). Other than numerous pathogenic opportunistic species were isolated (*Alternaria infectoria, Alternaria tenuissima, Epicoccum nigrum, Purpureocillum lilacinum, Cryptococcus laurentii*), many other environmental opportunistic fungi belonging to the genera *Penicillum, Aspergillus, Cladosporium, Mucor, Stemphylium, Conidiobolus* and *Trichoderma* were found. Bacterial densities in bioaerosol ranged from 9 to 174 cfu/m^3 with the highest values characterizing an emergency room. *Staphylococcus aureus* and other opportunistic *Staphylococcus* species were isolated in many areas. Several bacterial opportunistic species were also recovered (*Leclercia adecarboxylata, Enterobacter cloacae, Bacillus cereus and Kokuria varians*). In general, a moderate microbial pollution affected the examined surfaces with the exception of a massive bacterial density (>1 × 10^3 cfu/cm^2) observed on a drug carriage where *Pseudomonas stutzeri*, opportunistic pathogenic bacteria, was isolated as prevalent microbial species (Bonadonna et al. 2015).

Although recommendations exist, there is a regulatory lack of a referential standard for microbiological parameters of indoor air quality in healthcare facilities because of the deficiency in the relationship between microbiological survey data and their epidemiological implications.

Surfaces as Potential Sources of Infection

In hospital rooms, the surfaces are frequently contaminated with pathogens able to survive for a long time on room surfaces (beds, sheets, floors, walls and furniture) and medical equipment (de Oliveira and Damasceno 2010; Capolongo et al. 2013).

Biological agents may be transmitted to the patients by personnel gloves and visitor hands or through dust that, once deposited on the surfaces, may be contaminated and then resuspended by natural convection or conditioning air systems.

Hospitalization in a room in which the previous patient had been colonized or infected with methicillin-resistant *Staphylococcus aureus* (MRSA), vancomycin-resistant enterococci (VRE), *Clostridium difficile*, multidrug-resistant *Acinetobacter*, multidrug-resistant *Pseudomonas* or yeasts as *Candida auris* can represent an additional risk factor for the next patient admitted to the room.

The most relevant nosocomial pathogens persisting on dry inanimate surfaces and the duration of their persistence are reported in How long do nosocomial pathogens persist on inanimate surfaces? A systematic review by Kramer et al. (2006). Gram-negative bacteria persist longer than gram-positive bacteria. Moisture improves the persistence for several types of bacteria (e.g. Chlamydia trachomatis, Listeria monocytogenes, Salmonella typhimurium, Pseudomonas aeruginosa and Escherichia coli) while only Staphylococcus aureus persists longer at low dampness.

Prevention

No health-based standards or exposure limits for indoor biological agents exist. Differences in season; climatic and meteorological conditions; type, construction, age and use of the building and ventilation systems; and differences in measurement protocols used in the various studies (e.g. viable versus nonviable microorganism sampling, sampler type and analysis) make it difficult to interpret sampling data relative to information from the medical literature (Alfonsi et al. 2014).

These difficulties are exacerbated in hospitals where the patient health status, the activities that take place and the potential spread of pathogenic biological agents increase the level of complexity respect to other indoor environments. Moreover, the global burden of healthcare-associated infection is unknown because of the difficulty of gathering reliable diagnostic data.

The definition of the role that the environment has on the acquisition of hospital infections is highlighted by the need for multiple strategies to control the dissemination of pathogenic microorganisms and the adoption of prevention measures.

Because nearly 10^6 skin flakes containing viable microorganisms are shed daily from normal skin, it is not unexpected that patients—through gowns, bed linen, bedside furniture and other objects close to them—become contaminated with other patient flora.

The clarification of the role that surfaces have in the spread of infections could provide support to increase adherence to control measures. Improving and intensifying the cleaning routine may reduce the dissemination of pathogens. More attention should be given to the adequacy of the length, the frequency and specific care when cleaning surfaces, because removing dirt helps to reduce biofilms. The spread of pathogens could be prevented by using engineering and environment control strategies. Thus, in addiction to cleaning and disinfection standard procedures, the maintenance of appropriate hygienic targets may be obtained by employment of durable antimicrobial materials, such as copper and copper alloys (brasses and bronzes), especially for high-touch surfaces.

Antimicrobial copper touch surfaces can lower the number of microbes on surfaces, reducing the risk and preventing the transfer of antibiotic resistance between bacterial species (Michels et al. 2015; Gião et al. 2015).

Cause of microbial biocide multiresistance issue, in recent years new sanitation procedures, based on the use of probiotic products, have been studied. This technique connoted as biostabilization is based on the principle of competitive microbial exclusion and does not imply a biocidal action. Surfaces sanitizing probiotic products containing vegetative and spore forms of *Bacillus* species, in association with good hygienic practices, seem to provide 80–90% reduction of pathogenic agents and more than 60% reduction of infection events (Mazzacane et al. 2014; Caselli et al. 2016).

In order to avoid infections caused by airborne microorganisms, it is very important to maintain protective barriers that control the microbiological quality of the air. For aerosolized waterborne pathogens, faucets are easily accessible for

preventive measures, and the installation of single-use filters on hospital water outlets appears to be an effective concept to reduce water-to-patient transmissions of nosocomial pathogens.

Infection control programs have been defined by WHO and the Centres for Disease Control. The improvement of the surveillance systems for hospital infections and the implementation of standard procedures for reduction of microbial spread represent the main commitments (WHO 2011; CDC 2003).

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Legionella Indoor Air Contamination in Healthcare Environments

Maria Teresa Montagna, Osvalda De Giglio, Maria Luisa Cristina, Roberto Albertini, Cesira Pasquarella, GISIO-SItI Working Group, AIA Working Group, and SIMPIOS Working Group

Introduction

Legionella spp. is a ubiquitous intracellular microorganism present in aquatic environments both natural (e.g., rivers, lakes, and ponds) and artificial (e.g., potable water systems, taps, showers, cooling towers, and fountains). In particular, health care facilities, including hospitals, health centers, hospices, residential care

M.T. Montagna (✉) · O. De Giglio
Department of Biomedical Science and Human Oncology—Hygiene Section, University of Bari "Aldo Moro", Piazza G. Cesare 11, Policlinico, 70124 Bari, Italy
e-mail: mariateresa.montagna@uniba.it

O. De Giglio
e-mail: osvalda.degiglio@uniba.it

M.L. Cristina
Department of Health Sciences, University of Genoa, Via A. Pastore, 2, 16132 Genoa, Italy
e-mail: cristinaml@unige.it

R. Albertini
Department of Clinical and Experimental Medicine, University of Parma, Via A. Gramsci, 14, 43126 Parma, Italy
e-mail: roberto.albertini@unipr.it

C. Pasquarella (✉)
Department of Biomedical, Biotechnological and Translation Sciences, University of Parma, Via Volturno, 39, 43125 Parma, Italy
e-mail: ira.pasquarella@unipr.it

GISIO-SItI Working Group
GISIO-SItI (Italian Study Group on Hospital Hygiene-Italian Society of Hygiene, Preventive Medicine and Public Health), Viale Città d'Europa, 74, 00144 Rome, Italy

AIA Working Group
Italian Association of Aerobiology, Via delle Fonti, 10/7, 50018 Scandicci, Florence, Italy

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facilities, dental settings, and dialysis units, represent an at-risk environment for Legionnaires' disease transmission because of plumbing systems frequently old and use of medical devices from immunocompromised patients (Cristina et al. 2009; Spagnolo et al. 2013).

The microorganism grows at temperatures 25–50 °C, especially if the water is stagnant and rich in sediments, and it is responsible for various clinical manifestations, including pneumonia known commonly as Legionnaires' disease (WHO 2007).

The genus *Legionella* includes 59 different bacterial species and 70 serogroups (sg). Although *Legionella pneumophila* (*Lpn*) sg 1 and sg 6 are the main causes of disease, other species, e.g., *L. cardiaca* and *L. nagasakiensis*, have recently been associated with cases of legionellosis (Ministero della Salute 2015; Capolongo et al. 2013a, b). The disease normally occurs after inhaling an aerosol produced from contaminated water sources. Although one case of human-to-human transmission has been recently reported, many doubts are still upraised about this possibility, so it can be presumed that the environment is the only documented source of the infection (Correia et al. 2016; Buffoli et al. 2014b).

Since 2000, some international and national documents related to the control and prevention of Legionnaires' disease have been issued (WHO 2007; Ministero della Salute 2015), providing for the sampling of different environmental matrices (water, fouling, deposits, etc.), but not air. To date, the control on water mains is preferred, probably because of the ecological characteristics of the microorganism that recognizes, as a habitat, aquatic environments. In this context, it becomes more likely not only to detect the degree of water contamination but also to trace the source of infection, if the circumstances are favorable. However, air sampling could be a useful tool for exposure evaluation and efficient air sampling. This combined with water surveillance is considered beneficial for preventing legionellosis (Chang and Hung 2012). Some authors have shown the presence of *Legionella* spp. in samples of air both indoors (Pasquarella et al. 2010; Chang and Chou 2011) and outdoors (Crimi et al. 2006; Blatny et al. 2008), highlighting the difficulties in detecting *Legionella* spp.

Air Sampling

Counting microbes in the air is not an easy task. While procedures for the microbiological assessment of other environmental matrices are established in European law (e.g., methods are specified for the identification of microbes from water samples), there are no established regulations for air monitoring in health care environments.

SIMPIOS Working Group
Italian Multidisciplinary Society for Infection Prevention in Healthcare Facilities, Via C. Farini, 81, 20159 Milan, Italy

To sample biological particles in the air, active and passive methods can be used (Pasquarella et al. 2008; ISO 14698-1:2003).

Active Sampling

The active method works drawing a known volume of air and projecting it against a collecting surface, which can be solid or liquid. The concentration of microorganisms in the air is then measured and expressed in colony-forming units per cubic meter (cfu/m^3) (ISO 14698-1:2003). At present, different types of devices are commercially available, each with limitations, so that the choice must be based on the careful consideration of the objective of the sampling and knowledge of the limitations of the various samplers and all the factors which can affect the air sampling results (ISO 14698-1:2003; Pasquarella et al. 2008).

Each active sampler gives different results when used simultaneously for the evaluation of the microbial air contamination, showing a high variability. Many papers have been published, in which the efficiency of different samplers is evaluated and compared, but the final counts differ from one device to the other (Pasquarella et al. 2008; Chang and Chou 2011). So, it is difficult to compare data collected using different samplers.

The impact method on solid surface is the most common active method used for airborne microorganism evaluation. The impactor samplers differ in their inlet characteristics and can be divided into slit samplers and sieve samplers. In the former, air is drawn through a single nozzle, while in sieve samplers, air is drawn through a plate with several nozzles and the particles impact on a surface located below the perforated plate. The collection surface is usually an agar medium for culture-based analysis or an adhesive-coated surface that can be analyzed microscopically.

The surface air system (SAS) is one of the most used active sieve air samplers. It usually collects 180 L/min of air, blown on to 55-mm-diameter RODAC plates, containing a nutrient agar medium specific for the microorganisms to be detected. Some authors reported the SAS use to value *Legionella* indoor air contamination in dental clinics (Pasquarella et al. 2010, 2012a; Baglioni and Capolongo 2002).

The samplers on solid surface are very useful at low levels of airborne microorganisms; their performance can be adversely affected by overloading when microbial concentrations are high, resulting in agar plates or strips containing overlapping colonies that are too numerous to count.

In the case of a high level of airborne microorganism concentration, impingers are commonly used. Incoming air gurgles in a physiological solution or liquid culture medium, which is then filtered, and the filter is transferred to agar. For analysis, the liquid sample can be concentrated by filtration or diluted by liquid

addition. The sample can also be divided, and several analysis methods can be used (e.g., culture and molecular investigations). However, impingers can be inefficient in collecting large numbers of hydrophobic particles; in addition, the collected liquid may evaporate, particularly in hot dry environments.

In recent years, the *Impinger* method on liquid medium was considered as an effective tool for the detection of microorganisms in the air, particularly *Legionella* spp. (Deloge-Abarkan et al. 2007). Among the various active devices used, the Coriolis® μ allows to quantify *Legionella* spp. in bioaerosol (Langer et al. 2012). It is based on the action applied to the cyclonic airflow entering that, by generating a vortex, is pushed into the cone containing a liquid substrate; the particles are separated from the air and thus are concentrated in the collection liquid. The instrument is portable; it has a flow rate of 100–300 L/min and a drawing time from 1 to 10 min and is able to concentrate the microorganisms without stressing them.

Passive Sampling

Passive sampling method relies on the use of settle plates, being exposed to air for a defined period of time. It measures the rate at which viable particles settle on surfaces. Results are expressed in cfu/plate/time. However, in order to make comparable results from plates of different sized, the results should be expressed as cfu/dm^2/h (ISO 14698-1:2003). Passive sampling has been standardized with the definition of the index of microbial air (IMA) contamination, corresponding to the number of cfu's that are deposited on a 9-cm-diameter Petri dish containing nutrient agar left exposed to the air for 1 h (1 m above the floor, 1 m from the wall) (Pitzurra et al. 1997; Pasquarella et al. 2000).

Comparative Study Between Active and Passive Sampling

Several studies have compared the values of microbial counts obtained from active and passive sampling methods, with discordant results (Pasquarella et al. 2008; Napoli et al. 2012a, b; Buffoli et al. 2014a; Agodi et al. 2015; Montagna et al. 2014, 2016). Some authors found that a correlation between the two methods is possible when the active sampling is carried out at regular intervals during the exposure time of the settle plate (Perdelli et al. 2000), because a single drawing detects the contamination only during the short time necessary for the drawing and it is therefore not able to detect what the settle plates detected over the complete hour.

Legionella Air Sampling: the GISIO-SItI, AIA, and SIMPIOS Contributions

Based on this scientific background and our experience about Legionella spp. contamination and air microbial sampling in environments at risk of contamination/infection (Guarnieri et al. 1997; Pitzurra et al. 1997; Montagna et al. 2006, 2007; Napoli et al. 2010, 2012a, b; Buffoli et al. 2012; Pasquarella et al. 2010, 2011, 2012a, b; Capolongo et al. 2013a, b; Agodi et al. 2015; Astley et al. 2015; D'Alessandro et al. 2016), the Italian Study Group on Hospital Hygiene (GISIO) of the Italian Society of Hygiene, Preventive Medicine, and Public Health (SItI), in collaboration with the Italian Association of Aerobiology (AIA), promoted two multicenter studies focused on identifying a standardized sampling protocol to detect the airborne contamination coming from water sources contaminated with *Legionella* spp.

The aim of the first study was to compare active and passive sampling methods (SAS sampler, cfu/m^3 and settle plates, IMA, respectively) in detecting air *Legionella* contamination (Montagna et al. 2014). An experimental protocol on *Legionella* air contamination was carried out in a bathroom with a water supply

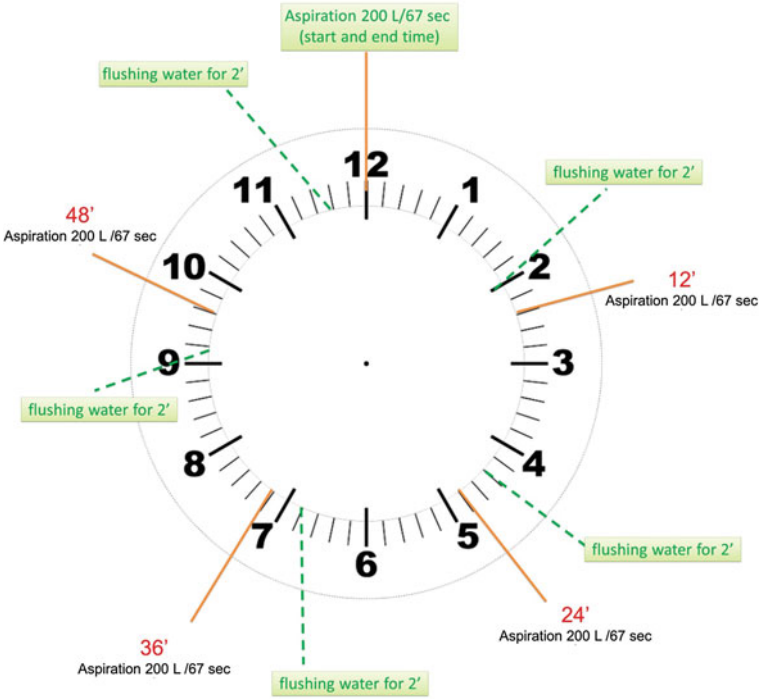

Fig. 1 Time schedule of first study focused on air sampling by active method

contaminated with >1000 colony-forming unit (cfu)/L of *Legionella* spp. Air contamination was assessed by the active and passive sampling methods for a total period of 8 h. Two hundred liters of air was sampled by SAS sampler every 12 min, after flushing water for 2 min (Fig. 1). The IMA value was calculated as the mean value of colony-forming units/16 plates exposed during sampling (2 plates/h). In parallel, the hot tap water was sampled three times (T_0 = before starting the first air sampling; T_1 = after 4 h; and T_2 = 8 h after the end of the air sampling). Overall, 10 Italian health care facilities were enrolled: Air contamination by *Legionella* was found in three health care facilities (one with active and two with passive sampling methods), showing a concomitant tap water contamination (median = 40,000; range 1100–43,000 cfu/L). The remaining seven hospitals isolated *Legionella* spp. exclusively from water samples (median = 8000; range 1200–70,000 cfu/L). Serological identification by monovalent antisera was performed on *Legionella* strains from water and air samples. *L. pneumophila sg* 6 was the most prevalent serogroup; it was found simultaneously in the air and water samples of three different health care facilities. In the remaining seven hospitals, *L. pneumophila sg* 1, 6, 7, 9, and 12 were isolated exclusively from water samples. The molecular investigation showed that *L. pneumophila* strains in the water and air samples of each positive health care facility had the same allelic profile. Strains, identified as sequence types (STs) 728 and ST1638 + ST1324, were isolated in two respective health care facilities, and a new strain, identified as ST1989, was obtained in one health care facility (Montagna et al. 2016).

After this study, GISIO-SItI in collaboration with AIA and Italian Multidisciplinary Society for the Prevention of Infection in Healthcare Organizations (SIMPIOS) carried out another larger multicenter study by comparing the same traditional sampling methods used in the first study (SAS sampler and settle plates) with an *Impinger* sampling by using the Coriolis® μ sampler. The operating protocol was modified by sampling the air with active samplers (SAS and Coriolis® μ) during and not after the 2 min of flushing water. Seven out of 11 health care facilities enrolled resulted negative by SAS and settle plates; one out of 11 resulted positive by SAS, one positive by settle plates method, and two positive by SAS and settle plates, simultaneously. Regarding active sampling method on substrate liquid by Coriolis® μ, all health care facilities enrolled were negative by cultural method, but eight out of 11 enrolled health care facilities resulted positive by molecular investigations. The preliminary results showed that both methods, active and passive, allowed *Legionella* to be detected in the air, although by using Coriolis® μ sampler no *Legionella* grow in culture media, while the molecular identification was positive in the majority of samples.

To date, there are no specific indications with regard to the protocol to be used in air sampling. Our data suggest that air detection of *Legionella* spp. cannot replace water sampling, since the absence of the microorganism in the air does not necessarily represent the absence of water contamination, but may provide the useful information for an adequate risk assessment.

Research Group

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Environmentally Friendly and Low-Emissivity Construction Materials and Furniture

Ilaria Oberti

Introduction

Creating a healing environment that nurtures the curing process requires paying attention to all that patients take into their bodies. In healthcare facilities, the administration of pharmaceuticals is a very strict action; primary interest is in what the patient eats, drinks and breathes: it ensures that the food is as healthy and balanced as possible, that the water is pure and it is drunk enough and that the outdoor air introduced in interiors is adequately filtered (D'Alessandro et al. 2016; Oppio et al. 2016). They are all correct and responsible actions, although, very often, the indoor air quality's monitoring is neglected (Settimo 2012).

The study, to date still the most complete, led by IEMB (Indoor Environment Management Branch, Internal Environment Management Section), a section of EPA (Environmental Protection Agency, Agency for Environmental Protection Environmental), in 1998 had the aim to analyse and determine the relationship between indoor and outdoor environments between the concentrations and exposures to different air pollutants, including gases and volatile organic compounds (VOCs). The data analysis supported the hypothesis that the indoor exposure to the most of the examined pollutants greatly exceeds the outdoor one, approximately from 10 to 50 times more; the indoor concentrations generally are from 1 to 5 times greater than outdoor ones.

I. Oberti (✉)
Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Via G. Ponzio, 31, 20133 Milan, Italy
e-mail: ilaria.oberti@polimi.it

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Although the deterioration of the indoor air quality cannot be attributed to a single cause, the main possible processes and factors that influence indoor air quality are as follows:

- lower attention of designers in the localization and orientation of the buildings, as well as in the choice of appropriate technical solutions and the application of base rules (Capolongo et al. 2013);
- measures for the reduction of the building energy consumption, such as better sealing and, simultaneously, a decrease of the ventilation;
- the use of innovative materials that are not enough tested and therefore strongly unhealthy;
- realization of lightweight constructions, appreciated for the low cost, for the operating speed and for the gain of usable area, but that inevitably require air-conditioning systems in order to ensure an adequate microclimatic comfort (Baglioni and Capolongo 2002; Morena 2015; Oberti 2014).

It is clear that the causes of indoor pollution are many and they are closely interrelated, and at the same time, it is possible to identify numerous types of pollutants' sources. They can include building materials, finishing products, furniture, etc., and they are particularly important for their large contribution. Some contaminants are derived from human activities and other types of pollutants, such as bacteria, moulds and bodily excretions, and derived from human, pets and plants present in living spaces. Other substances are emitted from building maintenance and cleaning products (Signorelli and Riccò 2012).

As stated by several authors, one of the main factors is also the configuration of the room, its size, their solar orientation, the size of the openings, etc.: within the same building, it is possible to have different air quality in relation to the various factors related to the building itself and its exposure (Settimo 2012; Pisello et al. 2014).

Today, in many hospitals, especially in inpatient wards, one of the parameters that greatly influence the daily life of users is lighting. Conventionally, the technology adopted for the windows of the rooms does not involve any innovative solutions: internal or external blinds shade, and very little customization is allowed to patient (Buffoli et al. 2007). In most of the new hospitals, as already happened in several hotels, windows cannot be opened by the patients, since it would introduce too many variables in the costs of heating and cooling of the healthcare facility (Capolongo et al. 2014); in fact, air circulation and heating are controlled by the HVAC system for managing costs best and for controlling the quality of air.

In summary, the indoor pollutants can be attributed to building materials, finishing products and furniture, HVAC (heating, ventilation and air-conditioning system), cleaning and maintenance products, the presence of people and their activities and, in healthcare facilities, medical equipment too.

A Focus on the Emissions from Building Materials and Their Effects on Health

The most important pollutants emitted from building products that arouse great concerns are volatile organic compounds such as formaldehyde, acetaldehyde, naphthalene, toluene, xylene, isocyanates and the semi-volatile organic compounds (SVOCs), such as phthalates and halogenated flame retardants (Bottero et al. 2015; Huisman et al. 2012).

Volatile organic compounds (VOCs) are carbon compounds that can become a gas at the regular room temperatures and after it will tend to evaporate from a building product into the air over time where humans can breathe it in. VOC-type chemicals are used as feedstocks for some plastics and utilized in binders and other resins for products such as composite wood or insulation; paints, coatings and adhesives; and the treatments to guarantee water resistance or to enhance stain repellence.

Building material finishes and furniture containing VOCs include resilient flooring, carpet, wall covering, fabrics, furniture, ceiling tiles, composite wood products, insulation, paints and coatings, adhesives, stains, sealants and varnishes.

In particular, formaldehyde is used as a binder in composite wood and batt insulation and in the fabric manufacturing process to protect fabric against shrinking, for improved crinkle resistance, dimensional stability and colour fastness. It is also utilized as a component of some finish treatments to improve stain resistance.

VOCs are often emitted at high levels when a product is first installed and diminish gradually to lower levels over time related to cure time or drying time, of components that are initially wet and finally dry (Tucker 2000).

Flooring, fabric, furniture and furnishings, namely solid materials, emit VOC emissions more slowly at first and maintain a low level of emissions over a longer period of time. Many VOCs have direct health effects as well. Some of these have been associated with short-term acute sick building syndrome symptoms, as well as other longer-term chronic health effects, such as harm to the liver, kidney and nervous systems, and augmented cancer risk (in fact, IARC—International Agency for Research on Cancer—considers formaldehyde as group 2A, instead benzene and acetaldehyde, as group 2B) (IARC 1987).

One of the VOCs of greatest concern is formaldehyde, classified as a Group 1-known human carcinogen by the International Agency for Research on Cancer (IARC 2004). The US EPA's Integrated Risk Information System (IRIS) estimates a cancer risk in humans of one in 10,000 at relatively low concentration levels (Beck et al. 2016; EPA 2015). Exposure to formaldehyde is also associated with decreased lung function and respiratory, eye, nose and throat irritation.

On the contrary, semi-volatile organic compounds (SVOCs) are compounds with higher vapour pressures than VOCs and they are released as gas much more slowly from materials. Moreover, they are likely to be transferred to humans by contact or by attaching to dust and being ingested.

Semi-volatile organic compounds are used in building materials to afford flexibility, in particular phthalates, water resistance or stain repellence, in particular, perfluorochemicals, as well as to inhibit ignition or flame spread, especially the halogenated flame retardants. Phthalates are found in soft polyvinyl chloride (PVC) building products, including vinyl flooring, upholstery, wall coverings, hospital and shower curtains. But they are also used in non-building materials, such as medical devices including tubing, blood bags and catheters.

Perfluorochemicals can be found in carpets, upholstery, textiles and furniture; in other situations in which stain resistance or water repellence are required, halogenated flame retardants are found in fabric and furniture, electronic equipment and foam pillows.

The concerns in indoor contamination by SVOCs are increasing because they can alter the hormones' activity in humans and wildlife, well known as endocrine disrupting chemicals (EDCs). They are suspected to contribute to the neurological and behavioural development, reproductive abnormalities, metabolic disorders and cancer (Weschler and Nazaroff 2008).

As regards, instead, physical contaminants' issues and fibrous insulations, under certain stress conditions, could be responsible for releasing mineral fibres into the air, so much more dangerous to health because their diameter is shorter and more easily breathable.

Heavy metals are other physical pollutant cause of concerns. They belong to the group of metallic elements extracted from mined ores that can be highly toxic in their elemental form or in compounds. Some of the ones that have raised most worries about human toxicity comprise arsenic, antimony, cadmium, chromium, copper, cobalt, lead, mercury and zinc. Heavy metals are used as stabilizers in vinyl plastic materials, that can be found in resilient flooring, ceiling titles coatings, window treatments, wall covering, carpet backing. In several building systems, and then also in healthcare facilities, heavy metals can be found throughout:

- it is possible to found lead in copper and other roof products, solder and batteries and in some PVC products such as wire insulation jacketing and exterior cladding;
- mercury can be in thermostats, switches and fluorescent lamps;
- chromium VI can be traced in chrome or stainless steel components of furniture;
- cadmium, cobalt, antimony trioxide and other metals may be incorporated into paint, dyes and pigments; fabric; and some PVC products such as resilient flooring.

Since heavy metals bioaccumulate and often are integrated in water system, human exposure becomes a criticism. Lead and mercury are potent neurotoxicants, particularly damaging the brains of foetuses and growing children (Martuzzi and Tickner 2004; Schettler et al. 2000). Cadmium is a carcinogen that can damage the kidney and lungs (Schettler et al. 2000); instead, chromium VI or hexavalent

chromium is listed by the International Agency for Research on Cancer, as a carcinogen (IARC 2004).

The health effects influenced by exposure to indoor pollutants affect patients, staff and visitors. However, these effects indent not only building occupants, but also the broader community, because some building products used outside can release contaminants, such as fibres and particulates, contributing to smog formation. The effects do not finish with the local community: design decisions play out across the whole life cycle of the materials used into healthcare facilities, beginning with the extraction of the raw materials and their manufacture into building products and medical products till end of life. The life cycle analysis of the materials could often a negative picture of the same specific material and the polymeric materials, widely utilized both finishes and medical equipment due to their high performance, constitute a representative example.

Drilling for the oil and gas from which plastics are made emits cadmium, mercury and a large quantity of other toxic chemicals such as xylene, arsenic, chlorophenols and polycyclic aromatic hydrocarbons into the environment. The harmful releases go on at petroleum refineries, which emit naphthalene, lead and other toxic chemicals. The track of toxic chemical emissions goes on at each subsequent step along the path to manufacture a final plastic product. The production of PVC alone contributes releases of dioxins, ethylene dichloride and vinyl chloride monomer. End-of-life disposal proceeds the matter with the release of yet more toxic chemicals (Alfonsi et al. 2014).

The Choice of Green Materials

Improving indoor air quality and avoiding materials responsible for some of the worst toxic chemicals released into the environment should be the top priorities during the design decision-making, evaluating environmental performances of building materials (Buffoli et al. 2015; Oberti 2013a). It is fundamental to define what are environmentally preferable for green materials. Although there is not yet a definitive set of materials and product standards that define it, the scientific community converges on some basic criteria, so that the products or systems should have or be:

- **recyclable**. Products are manufactured all or in part with recycled materials and can also be recycled after use. Using recycled products or products with recycled content is environment-friendly and supports the economy in several ways. A significant effect can be the decreasing need for manufacturing with virgin and non-renewable resources, which saves precious resources and also saves manufacturers' investment. Materials that would have ended in landfills after its useful life instead can be reprocessed for use in other products. For example, newspapers can be reprocessed into cellulose insulation; plastic milk cartons can

be shredded, melted and reprocessed into toilet partitions; and rubber from automobile tyres can be reprocessed into roofing and flooring materials;

- **renewable resources**. Products are made with renewable resources rather than non-renewable. Depletion of the Earth's resources is occurring at an alarming rate. By utilizing renewable energies, such as wind, solar, tidal, as well as renewable products, such as wood, grasses or soil, it is possible to reduce the impact on biodiversity and ecosystems (Brambilla Pisoni et al. 2009);
- **minimum waste**. Products produce as little waste as possible in their manufacture, use and disposal. Buildings are big generators of waste: landfills are overflowing, especially with construction waste, which accounts for 40% of the usage at landfills. By utilizing methods of reuse and recycling of scrap and trimmings, employing strategies that minimize waste through the life cycle of a product, manufacturers can radically reduce the amount of products that are put into the waste stream (Bottero et al. 2015);
- **locally or regionally produced**. Products manufacture closer to their use (within 350 km), produce less pollution in transportation and also support regional economies (Bottero et al. 2015);
- **low embodied energy**. Vast amounts of energy are used in the production of building materials. The embodied energy of a product, sometimes, involves a complex series of processes that contribute heavily to the indoor pollution, the depletion of natural resources and the degradation of the earth. This embodied energy includes the energy necessary for extracting minerals and raw materials, the fuel necessary for transporting materials to the manufacturing site and the energy used at the plant to make the final products. Moreover, it includes the energy during the use and, later, disposal of the product (Brambilla Pisoni et al. 2009; Paleari et al. 2012);
- **low environmental and human impact**. They are products that do not harm the environment, but cause air or water pollution or damage to the Earth, its inhabitants and its ecosystems in their manufacture, use or disposal. They are non-toxic and contribute to good indoor air quality, because they are produced in accordance with the twelve principles of Green Chemistry (Anastas and Warner 1998). Pollution caused in excavation, manufacture, use or disposal of a product can have untold consequences on ecosystem. Poor indoor air quality, caused by products emitting harmful substances, increases the risks to people's health;
- **durable**. They are products that are long-lasting and need little maintenance. Product replacement puts a strain on the earth, its resources and its inhabitants. In making products more durable and easy to maintain, manufacturers permit to eliminate costly, damaging and time-consuming processes of replacement (Buffoli et al. 2012; Capolongo et al. 2016).

It is impossible thinking that building industry changes suddenly, but some signals indicate an improvement: there are alternatives already on the market that

illustrate the potential for greater sustainability and healthier products (Faggioli and Capasso 2015). In any case, considering all the possible constraints, for reaching sustainability in health care, the designers should focus the attention on the main components, which, if correctly designed, can drastically increase the overall (economic, social and environmental) performance of the facility. Currently, as Guenther and Vittori reported, there are many case studies that adoperate sustainable materials with different strategies (Guenther and Vittori 2014).

One of these alternatives is non-toxic plastic for its chemistry and renewability. Instead to be made from limited virgin material, like fossil fuels, they are originated by sustainable biobased resource; it is recyclable closed loop and, finally, biodegradable into healthy nutrients for food crops.

Plastics made from plants, called biobased plastics, are the new generation of plastic materials; such as the plastic, polylactic acid (PLA) is manufactured from corn rather than fossil fuels. Biobased plastics, such as PLA, have been in use for some time for select medical products and now they are starting to be utilized in fabrics and internal finishing materials such as wall protection systems and carpet. Linoleum flooring, wood cabinetry, cotton insulation and other biobased materials can be placed on the spectrum similarly to biobased plastics. Biobased materials are favoured over fossil fuel-based products for a wide variety of reasons: from their potentially inexhaustible renewable nature to the reduced global warming impact and avoidance of the environmental and human health impacts of fossil fuel exploration, extraction and refining (Oberti 2013b).

A further step in the research of sustainable strategies can be the use of natural fibres in insulation. Commonly, vegetable and animal ones are quite widespread, although these kinds of solutions are diffused in civil architecture, but not in hospital planning. Even though this criticism deficiency can be related to the suspicion on some hygiene related issues, currently there are several international companies that are developing healthy natural materials, already studied and certified.

The healthcare institutions have a very important leadership role in the decision-making of construction materials (Capolongo et al. 2014). Building materials' selection is an important phase, especially for in-design hospitals or renovating activities, for reaching social and environmental sustainability, as several authors assert (Edwards 2010; Buffoli et al. 2015). It is influenced both to maximize environmental sustainability and to respect safety and comfort levels for users.

With important market power and the Hippocratic oath of "first do no harm", health cares and other health systems are leading attempts from within the sector to source healthier building materials, to avoid products enclosing dangerous chemicals connected to cancer, respiratory problems and other hazardous health effects and to commit innovative strategies to move the market to research, develop and safer produce products.

Prevention is a fundamental principle of health care and public health. In the face of dubiety, precautionary action is appropriate to prevent injury. This public health

approach makes sense both in the clinical setting and in responses to environmental and public health hazards. Similarly, a precautionary and preventive approach is an appropriate basis for decisions concerning material selection, design features, mechanical systems, infrastructure and operations and maintenance practices (Capolongo et al. 2016).

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HVAC System Design in Healthcare Facilities and Control of Aerosol Contaminants: Issues, Tools, and Experiments

Cesare Maria Joppolo and Francesco Romano

Indoor Air Quality in Healthcare Buildings

Healthcare buildings (HCBs) like conventional buildings need some forms of indoor climate control, in terms of temperature, humidity, and air quality. Heating, ventilating, and air-conditioning (HVAC) systems in buildings are leading to indoor environment quality and exert a key role in occupant's comfort and health. In the HCB context, indoor air quality requires by far the greatest attention: to ensure a healthful indoor air quality (IAQ) is widely recognized as a mandatory goal in HCBs to protect the patients and healthcare workers against hospital-acquired infections (HAI) and occupational diseases. It is worth noting that not the thermal comfort issues but IAQ, the ventilation needs, and the interactions between air movements and dispersion of contaminants are becoming the key factors within the context of HCB services design and operation. IAQ is really a determinant of building design and has impacts on the societal values such as people's health and energy use. However, the problems with measuring and defining what is "good IAQ" are multimodal and unprecedented and require a multidisciplinary approach in order to find new and adequate solutions. Let us stress that we are at a turning point in IAQ. Until now, we have relied on prescriptive codes dictating quite simple but indirect physical quantities such as target air flows (per person or per floor area), air changes per hour (ACH), or pressure differences and specifying some features of equipment (e.g., air filter efficiency) and of the building (e.g., air tightness of the envelope, and low-polluting materials). There is at the moment a quite limited use of air quality sensors, and therefore, HVAC design and operation are based on inadequate knowledge of contaminant presence and of their

C.M. Joppolo (✉) · F. Romano
Department of Energy, Politecnico di Milano, Via Lambruschini, 4, 20156 Milan, Italy
e-mail: cesare.joppolo@polimi.it

F. Romano
e-mail: francesco.romano@polimi.it

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spatial and temporal concentrations. Technical advancement and cost reduction of IAQ sensors (notably low-cost optical particle counter, OPC, for particle concentration) and of computerized simulation tools (CFD) and the wide adoption of Internet of Things (IOT) technologies will allow the shift to performance-based concepts for ventilation and to customized/personal solutions that acknowledge the primacy of healthy indoor air measurements.

Ventilation for hospitals is a very broad and complicated field: ventilation has to serve a large number of different spaces and processes, many with special requirements that cannot be met without special considerations. There are many different approaches and recurrent options as follows: (1) natural ventilation versus mechanical and hybrid ventilation; (2) outdoor air only (no recirculation) versus secondary/recirculation air systems; (3) ventilation rate per person (or per emission source) versus air changes per hour (ACH); and (4) concentration limits for particles (particles/m^3) and/or for microbiological contaminants (CFU/m^3). Moreover, HCB ventilation is ruled by binding national laws and regulations, but is technically driven by a multiplicity of standards and guidelines that are voluntary and an expression of the state of art, pertaining to different geographical areas [e.g., local, national, European, and international (FGI 2014; CDC 2003; WHO 2009; ASHRAE 2014)].

In order to rightly address the goals of IAQ future issues in HCBs, we should bear in mind the rising concerns for antibiotic resistance and therefore the increasing need to use ventilation as an effective way to control infection in hospitals. But, at the same time we cannot ignore the HCB massive energy consumption and the strong push to save energy and reduce hospital's carbon footprint. Aiming to contribute to the mentioned goals, this paper describes current technologies and encourages using novel approaches and not very often employed tools (i.e., particle measurement, and CFD simulation).

Aerosols, Particles, and Microbial Contamination

In the indoor environments, people are emitting all types of air contaminants (particles, microbial contaminants, gas, and vapors) but they are the main source of particles and of microbial contaminants. The relationship between people and indoor particles and microbial contaminants is complex due to the two different mechanisms that are involved (Tang et al. 2009; Tellier 2009; Morawska 2006). First, people generate particles; they eject saliva droplets and release the outermost layer of skin. Second, people carry particles and spread them; they contact various surfaces and this may lead to a possible cross-contamination. In fact, the main source of particles released by people is due to the shedding of the outermost layer of epithelial cells: every 24 h this amounts to about 1,000,000,000 flakes (10^9 particles per day). A proportion of these will carry colonies of the bacteria that grow in skin. The rate of shedding increases with movement, and the release into the air is related to the type and extension of clothes worn by people. The average skin cell is

a flake of about 33 μm × 44 μm in surface area and about 3–5 μm thick. The skin flakes may be found in the environment either as whole cells or fragments. Microorganisms grow on the cells and skin glands and are dispersed into the air on skin detritus. These particles are called microbe-carrying particles (MCPs). The MCPs may have various sizes, shapes, and densities. Various authors have investigated the equivalent particle diameter of MCPs dispersed from people, compiled these results, and reported consensus that the MCPs' average size is about 12 μm.

Human–human disease transmission can result from direct and/or indirect contact with an infected person, but the transmission can also be airborne. Direct contact means any surface contact such as touching, contact with oral secretions or skin lesions, and routes such as blood transfusions or intravenous injections. Indirect contact involves contact with an intermediate inanimate surface, such as a doorknob or bedrail that is contaminated. We cover here just the airborne transmission, which occurs through large droplets, falling by gravity in a short time and distance from the emission, and small particles, which can stay airborne for hours and can be transported at quite long distances (ASHRAE 2014).

As far as large droplets are heavy, they settle down quickly and the ventilation system (dilution, pressure differentials, and exhaust) has a limited influence on their ability to hit a target person and to transmit pathologies unless they reduce diameter by evaporation, thus becoming a fine particle aerosol (the term "droplet nuclei" has been used to describe the desiccation of large droplets into small airborne particles). The important mode of person-to-person disease airborne transmission is by fine particles that contain the microorganisms (small droplets and droplets nuclei, skin flakes, fungal spores, resuspension from surfaces, etc.) and can travel in room air over long distances and time scales. The size demarcation between large droplets and small particles has been described as having an aerodynamic diameter of 2.5–10 μm, but even particles with a diameter of 30 μm or greater can remain suspended in the air. Tang et al. (2009) proposed a scheme considering the particles as large droplets if the diameter is greater than 60 μm, small droplets when diameter is smaller than 60 μm, and droplet nuclei when diameter is smaller than 10 μm. However, the exact size demarcation is less important than knowing that large droplets and small particles behave differently, that the latter can remain airborne, and that medium size and fine particle aerosol concentration are heavily influenced by air movements and ventilation design and operation. There are hundreds of airborne communicable pathogens falling into three major categories: viruses, bacteria, and fungal spores. Viruses are the smallest with diameters of 0.02–0.3 μm. Bacteria have diameters in the range of 0.5–10 μm. Spores are the largest with diameters in the range of 0.5–30 μm. It should be noted that the dimensions of the pathogens are different from the dimensions of airborne particles (droplets, skin flakes, etc.) carrying them and originated by people and human activities (e.g., sneezing, showering, flushing, sewage aerosolization from toilets, bed making, bronchoscopy, autopsy, and surgery). It should be also highlighted that the aerosolization process can create fluid shear stresses and inactivate some pathogens. The viability of a pathogen changes as a function of various environmental conditions (e.g., temperature, humidity, ozone concentration, and light and electromagnetic radiation), and the infectious disease

process depends on the pathogen concentration and virulence that enable to override the physical and immunologic host defenses.

Let us concentrate on how the ventilation can be important in HCBs for controlling (1) aerosol disease transmission in general and specific clinical areas and (2) surgical site infections (SSI) in operating theaters (OTs):

1. The aerosol disease transmission is known to be the main route for many diseases such as tuberculosis and aspergillosis. Recent research has shown a great importance of aerosol infection for common diseases such as influenza, especially during cold and dry seasons. For example, modern experimental techniques have detected infectious aerosols produced by infected patients while breathing, coughing, or sneezing (Azimi and Stephens 2013; Miller-Leiden et al. 1996).
2. Surgical site infections (SSIs) are infections that occur in the wound created by an invasive surgical procedure. SSIs are one of the most important causes of healthcare-associated infections and are caused by airborne contaminants. Therefore, OT are among the most infection-sensitive environments in healthcare facilities. Surgeries increase patient's vulnerability to pathogens transmitted from surgical personnel, patient's own skin flora, surgical equipment, and the air. With respect to bacteria transmitted to the surgical site through the air, skin scales and their settling on the surgical site are the primary source of transmission. Whyte et al. (1982), and Lidwell et al. (1983) have shown the important correlation between the airborne wound contamination and the ventilation system. In particular, they have established a linear relationship between the level of bacterial air contamination and the frequency of deep sepsis following surgeries.

Ventilation and Air-Cleaning

Because small particles remain airborne for some period of time, the design and operation of HVAC systems that supply, extract, and move air can affect the disease transmission in several ways as follows:

- supplying clean air to susceptible occupants;
- diluting the air in a space with cleaner air from outdoors and/or by filtering the air;
- containing contaminated air and/or exhausting it to the outdoors; and
- cleaning the air within the room.

The following ventilation options are of interest:

- dilution ventilation;
- filtration (central or unitary);
- air diffusion and in-room flow regimes (laminar);
- differential room pressurization;

- personalized ventilation and local source capture; and
- UVGI (in-room and in the airstream).

Ventilation represents a primary infectious disease control strategy through dilution of room air around a source and removal of infectious agents. The main method of reducing the time and/or number of microbes to which a person is exposed is by increasing the dilution rate of clean air into a space. This would normally decrease airborne contaminants and therefore pathogen concentrations, which would be expected to reduce the exposure time of microorganisms generated within the room by objects, staff, or the patient. The methods used for mechanical ventilation design can be schematically described as follows:

- source control;
- dilution (general and task-specific ventilation);
- particulate filtration (non-specific and effective on inorganic, viable, and non-viable organic contaminants);
- air diffusion (mixing, displacement, and unidirectional/laminar);
- moisture control (mold growth, bacteria, and virus); and
- air-pressure control.

Natural ventilation, such as that provided by user-operable windows, is not covered as a method of infection control by most ventilation standards and guidelines. There are very few studies on natural ventilation for infection control in hospitals. One guideline that does address it recommends that natural ventilation systems should achieve specific ventilation rates that are significantly higher than the ventilation rates required in practice guidelines for mechanical systems (WHO 2009).

Air Cleaners and Air Filters

Filters can effectively trap particulate contaminants, including microbiological pathogens, and remove them from the circulating air. Filter efficiency varies with particle size, so the type of filtration required in order to be effective varies with the type of organism and the aerosol (particle) that carries it. Various grades of filters can be used to achieve different degrees of cleanliness. For a healthcare facility, a proper filtration system generally consists of two or three stages of filtration (i.e., a prefilter and a final filter or a coarse and a fine filter in the AHU plus a final filter at the air diffuser). A coarse filter is placed in the AHU upstream, ahead of the cooling/heating coil, to remove large particles for a clean heat transfer medium and to prolong the life of the fine filter placed downstream, resulting in a cost-effective operation. The final filter should have at least 90 % efficiency to collect nearly all the fungal spores of 2–5 μm diameter and bacteria in colony-forming units of 1 μm diameter or larger.

In "critical" areas (e.g., OT or where there are immunocompromised patients), a high-efficiency particulate air (HEPA) filter with no less than 99.97 % efficiency on 0.3 μm particles should be used. Ultra-low penetration air (ULPA) filters at 99.999 % efficiency on 0.1–0.2 μm particles are also available. The addition of highly efficient particle filtration to central ventilation systems is likely to reduce the airborne load of infectious particles. This control strategy can reduce the transport of infectious agents within individual areas and from one area to another when these areas share the same central ventilation system (e.g., from patient rooms in hospitals or lobbies in public access buildings to other occupied spaces). Local, efficient filtration units (either ceiling mounted or portable, floor-standing) reduce local airborne loads and may serve the purposes in specific areas such as healthcare facilities or high-traffic public occupancies (Kujundzic et al. 2006).

Air Sampling and Concentration Measurement of Particles and Microbe-Carrying Particles

In order to assess the contaminants' presence in ambient air, a particle counter can be used. The particle counter measures all airborne particles and do not distinguish viable from non-viable particles. Particulate monitoring is normally done by a calibrated Optical particle counter (OPC), used to sample a defined volume of air. The OPC can measure a variety of particle sizes, most commonly 0.5 and 5.0 μm. Particle counts are recorded as the number of particles per volume of air sampled. In order to measure the viable airborne particulates, an active microbial air sampler (AMAS) is used to sample a defined volume of air, embedding viable particulates onto sterile media strips or dishes (Romano et al. 2015a, b). The media, embedding viable particles, are incubated to promote their growth, and the colonies of microorganisms are counted. The results are reported as the number of colony forming units (CFU) per volume of air sampled. The information resulting from the use of OPC and of an active microbial air sampler is complementary, and even if viable particles are a fraction of all airborne particles, there is no straight relationship between the two measurements (pp/m^3 vs. CFU/m^3). It must be highlighted that OPC measurements are quite simple to perform and they give immediate results. Therefore, OPC is a powerful tool to verify air quality and HVAC system performance. OPC can be used in situ to verify the filtration efficiency and dilution effects. The particle counts provide verification of filtration efficiency, and this could show the relative drop of both viable and non-viable particles (e.g., a >90 % drop of viable particles for 90 % efficient filter). The OPC can be used to establish some baseline data (based on particle removal) in HCBs, critical and non-critical area. Baseline OPC measurements should compare data from indoor space and outdoors, and they are useful to rank spaces from "dirty" to "clean". Last but not least, OPC measurement could be important in ruling out ventilation as a contaminant source. Let us summarize that OPC is a widely usable tool to quantitatively assess, monitor, and control hospitals' ventilation.

Viable and Non-viable Particle Release by People and Garments: Test Data and Impact

Personnel attire in HCBs and in OT should attempt to balance the professional appearance, comfort, and practicality with the potential role of apparel in the cross-transmission of pathogens resulting in healthcare-associated infections (HAIs). The goal of keeping MCPs and inert particles at a low airborne concentration, for a given source generation rate, is pursued by ventilation, supplying an appropriate airflow of duly filtered air and recurring to an appropriate diffusion scheme (mixing, displacement, or UDAF). But it is really important to recognize that, the people often being the most relevant indoor particle contaminant source, it is also effective and efficient to minimize the dispersion from the people using occlusive clothing and adopting clean space-access behavioral procedures. Type of garment and body coverage, clothing material and filter efficiency of fabric, cloth use and cleaning/washing frequency, wearing and deterioration, and changing procedure into and out of clean spaces are all therefore important aspects.

In the environments where personnel are the main source of contamination and almost the only source as for microbiological contamination, personnel gowned with appropriate technical clothing system may reduce the microorganism particles released into the air. Methodologies for assessing the performance of cleanroom clothing systems have been proposed and are used to measure separately the body release of total and viable airborne particles. Many works have studied the clothing performance in relation to pharmaceutical industry cleanrooms and, more recently, surgical clothing systems have been started to be investigated. Politecnico di Milano and Chalmers University have a cooperation agreement in this field, and they have installed two experimental dispersal chambers (body-box) for the measurement of the rate of both total and microbial airborne particle dispersion from persons wearing technical clothing system in cleanrooms and in OTs.

In fact, the likely airborne concentration in a clean-space can be calculated from a knowledge of the dispersion rate of MCPs and particles, as well as of the air flow to a room. The source strength q_s can be expressed either in terms of particles (for diameter ≥ 0.5 or ≥ 5 μm) released per unit time and per person or in terms of CFU per second per person and is a figure describing the protection efficiency against particle shedding of a clothing systems (Fig. 1). The simplest possible (steady-state, perfect mixing, and clean-air supply) balance expression applying the dilution principle to a room links the source strength q_s, the supply air flow Q, and the resulting contaminant concentration C as follows:

$$C = q_s/Q \tag{1}$$

The equation shows that the concentration and airflow measurement in a test dispersal chamber allow to quantify (Whyte and Hejab 2007; Ljungqvist and Reinmüller 2004) the source emission rate q_s.

Fig. 1 Dispersal chamber (body-box) at Politecnico di Milano

Table 1 Results of surgical and cleanroom clothing systems tested at Politecnico and Chalmers (source strength expressed as released aerobic CFU, particle ≥ 0.5 and ≥ 5 μm)

Source strength	Surgical clothing	Grade B cleanroom clothing
Aerobic CFU/person/s	7.8	≤ 0.23
Aerobic particles/person/s (≥ 0.5 μm)	41,562	2015
Particles/person/s (≥ 5 μm)	3357	31

Experimental tests have been carried out in the two body-box test rigs at Politecnico and Chalmers. Sample results are presented in Table 1 (Romano et al. 2016). They are indicative of the highly relevant effects of the clothes worn by personnel on the source strength (differences of one or two orders of magnitude) in

cleanrooms and OTs. Let us mention that a street attire would entail an additional tenfold to hundredfold increase in the source strength. Referring again to the simplest balance in Eq. 1 can be worth saying that in ventilated OT (or in other clean-spaces), when people are the dominant pollutant source, the obtained airborne contaminant concentration C depends directly on the contaminant release rate (source strength and number of persons) and on the supply airflow. So a tenfold decrease in the source strength could determine a tenfold increase in air cleanliness at fixed air flow or a tenfold decrease in airflow at fixed air cleanliness.

The OT Ventilation System: the CFD Simulation Tool Applied to a Case Study

As mentioned before, the shift to performance-based concepts for ventilation and to effective and energy efficient solutions is made possible by a wider use of IAQ sensors and of CFD simulation tools. Romano et al. (2015b) presented a case study that used both CFD simulations and experimental measurements to highlight the design issues, performance indicators (protection grade SG according to Standard DIN 1946-4 (2008), and operational test procedures (the reader can find all the details of the CFD simulation and of the experiment in the reference). The case study OT is provided with a unidirectional ceiling diffuser composed of 23 terminal HEPA H14 filters installed in a plenum of 3 m $\times$ 3 m.

The main characteristic of this ceiling filter system is the differentiation of the supply air velocity (0.45 m/s at the center, 0.35 m/s in the semi-periphery, and 0.25 m/s at the periphery). Let us mention that the design of a ventilation system for an operating theater is aimed to prevent the risk of infections during surgical operations. Surgical site infections (SSI) are often associated with airborne particles released by the human body, and their settling on the surgical site could be the cause of potential infections. The works of Stacey et al. (2002), Whyte et al. (1982) and Lidwell et al. (1983), and Charnley and Eftekhar (1969) have shown the important correlations between the airborne wound contamination and the ventilation system. In particular, they have established a linear relationship between the level of bacterial air contamination and the frequency of deep sepsis following surgery. In the case study by Romano et al. (2015b) two different scenarios have been studied to evaluate the protection level against the entry of external and internal contaminant loads into the protected area (Fig. 2).

In effect, both the CFD simulation and the experimental measurement have shown that the HEPA filters and the differential air flow diffusion system are able to maintain the desired protective effect (SG) against contamination load in both the

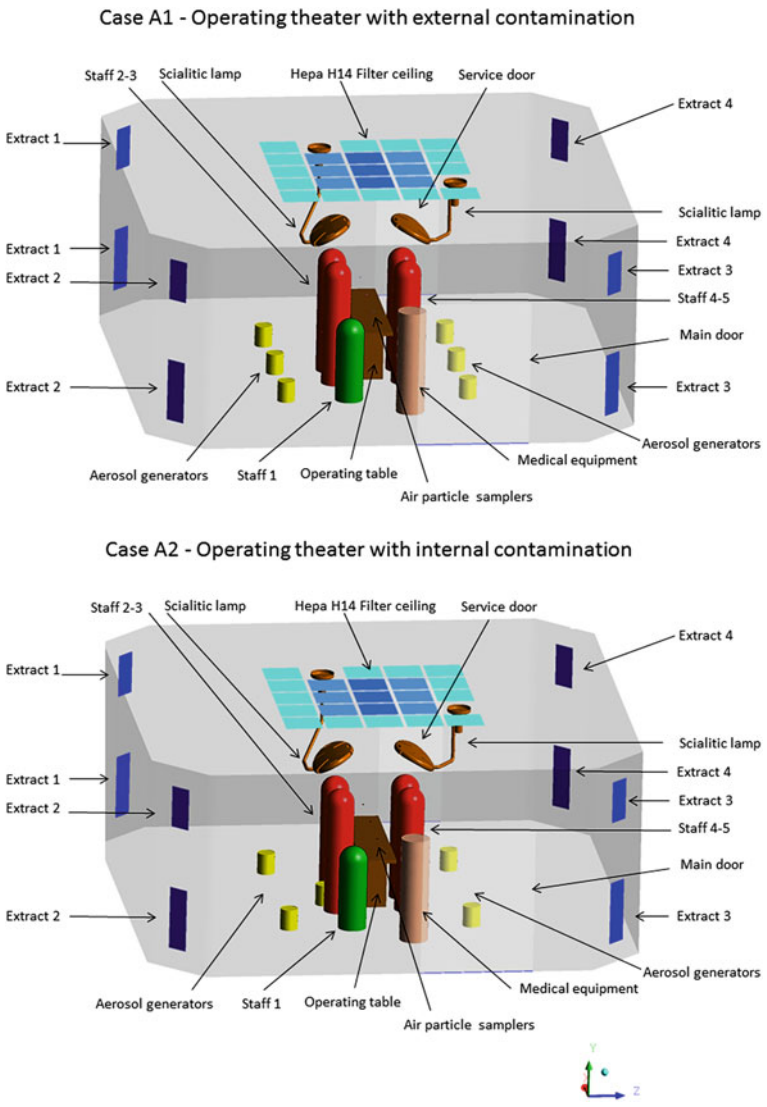

Fig. 2 OT layouts (Case A1, external contamination; Case A2, internal contamination)

design and the off-design conditions. The CFD tool, when adequately tuned, calculates particle concentration in the protected area in close agreement with the measured ones (Figs. 3 and 4).

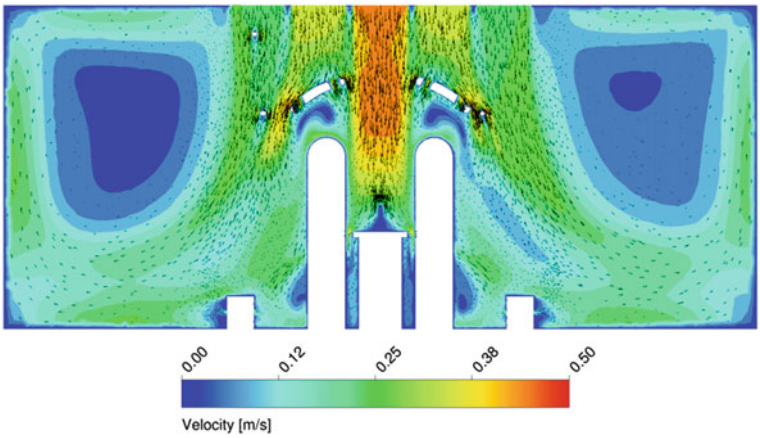

Fig. 3 Velocity vectors in the OT (CFD simulation, Case A1)

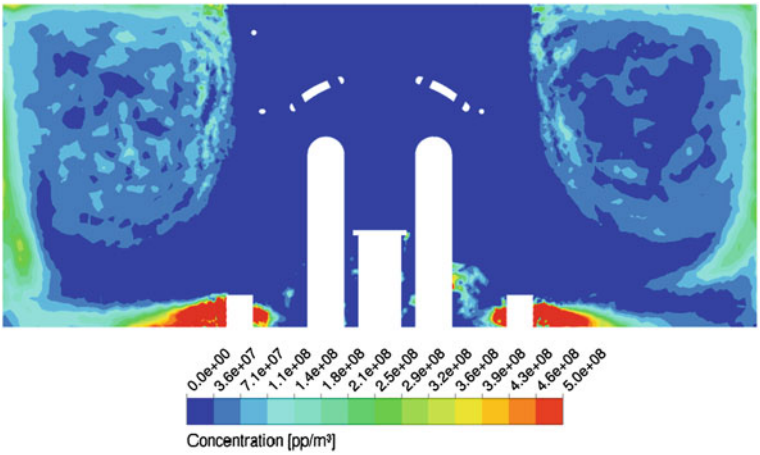

Fig. 4 Particle concentration contour in the OT (CFD simulation, Case A1)

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HVAC Management in Health Facilities

Umberto Moscato, Alice Borghini, and Adele Anna Teleman

Recent and progressive innovations in medicine and ancillary technologies determine the need to constantly re-evaluate the importance of the hospital microclimate and of air-conditioning systems. Scientific evidence has shown, more and more, that an appropriate air-conditioning (through the air filtration and the achievement of correct differential pressures between the environments at greatest risk) is useful not only in the prevention of several communicable diseases, but also in the reduction or elimination of the spread of physical and chemical contaminants (Astley et al. 2015; Capolongo 2016). On the other hand, it is equally true that the installation, maintenance and energy costs of Heating, Ventilating and Air-Conditioning (HVAC) systems have all increased over time. Therefore, for HVAC systems to be sustainable, they require a careful study of the design, a correct evaluation of the necessity of the installation in the place in question, and the requirement or, even better, the scientific evidence of their effective cleaning and maintenance, especially in environments in which there are patients with a depressed immune system or immunosuppression. Furthermore, health facilities are becoming increasingly diverse in response to a trend towards the increase in outpatient services and reduction in hospitalization time. For this reason, the air-conditioning in hospitals plays an increasingly important role compared to simple micro-climatic comfort (Capolongo et al. 2014). In many environmental risks, an appropriate climate control becomes an underlying factor in patient's therapy and in some specific diseases or treatments, the most important protection

U. Moscato (✉) · A. Borghini · A.A. Teleman
Public Health Institute, Hygiene Section,
Università Cattolica del Sacro Cuore,
Largo Francesco Vito, 1, 00168 Rome, Italy
e-mail: umberto.moscato@unicatt.it

A. Borghini
e-mail: alice_borghini@hotmail.it

A.A. Teleman
e-mail: ateleman@hotmail.com

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of the patient's health (e.g. prevention of surgical site infections in surgery, transplant surgery and subsequent hospitalization, containment of high contagiousness infections, and hospitalization and treatment for oncology patients). Several studies show that patients in climate-controlled environments generally have a faster and more effective physical improvement than those in uncontrolled environments. Some examples of this are cardiac patients with congestive heart failure, patients with rheumatoid arthritis, patients needing oxygen therapy and those with a tracheotomy (who require particular attention to ensure an environment in which the inspired air is hot and humid) (ASHRAE 1995; Kilbourne 1998; Capolongo et al. 2016). Dry air may be a risk factor for different diseases (e.g. of the upper respiratory tract) and can promote the development of secondary infections, infections correlated with the principal cause of hospitalization and nosocomial infections that can in turn become the major risk of death for the patient.

An appropriate air-conditioning is, therefore, useful for the prevention and treatment of various diseases, but the design, installation, operation and maintenance of HVAC systems in healthcare facilities have different problems that are not normally present in the equivalent HVAC systems designed for air-conditioning in residential or administrative environments. The fundamental differences between air-conditioning for hospitals, and correlated health facilities, and that for other building types are, among the others (ASHRAE 1995; Baglioni and Capolongo 2002):

- the various temperature, humidity, air speed and air exchange rate requirements for different departments and environments;
- the peculiar requirements for filtration, ventilation, exchange rate and differential pressure to dilute, to contain and remove microbiological, chemical and physical contamination in the form of odours, airborne microorganisms and viruses, hazardous chemical and particulate substances (drugs, chemotherapy and antibiotics scattered in the air, colony-forming units carrier particles, etc.);
- the design complexity needed to permit accurate control of environmental conditions, which determines low maintenance costs, facilitates the technical operations of cleaning and replacement of parts, which is energetically sustainable and eco-friendly and which allows to contain the air flows in and out between various areas.

The possible sources of airborne infections in the hospital are many and, therefore, while the HVAC system improves comfort and prevents the onset of many diseases, on the other hand, it can also be considered a vehicle of communicable disease transmission, due to its possible role in nosocomial infections (Fig. 1).

The use of the HVAC system can promote the transmission of all bacterial microorganisms that can be transmitted in the air (i.e. aerosols and droplets) or in the air and water mixtures. Some important examples of these microorganisms include not only *Mycobacterium tuberculosis, Legionella pneumophila,* but also many other Gram-positive and Gram-negative microorganisms. Droplets or

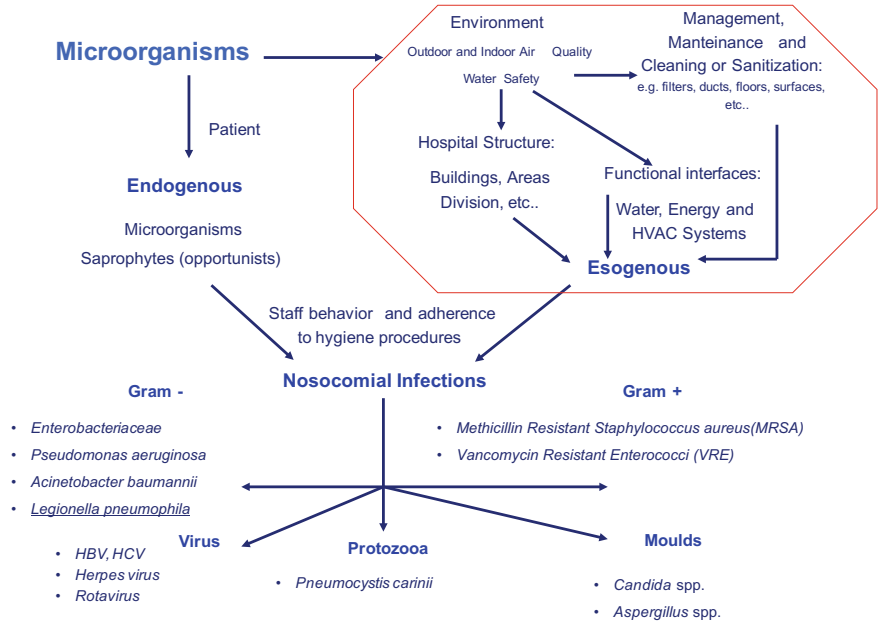

Fig. 1 Pattern of relationship between the sources, risk factors and transmission of microorganisms in the hospital: HVAC systems (not exhaustive example)

infectious agents that are of a size of 5 μm or less can remain airborne indeterminately and since bacteria are typically present in the colony-forming units that are larger than 1 μm, 99.9% of all bacteria present in air are removed by 90–95% efficient filters. Therefore, in some critical hospital environments such as operating rooms, intensive care units, isolation rooms (with a controlled microbial load) for transplantation or in other environments at risk of bacterial contamination of the patient, legislative and technical norms and standards recommend the use in HVAC systems of high-efficiency particulate air (HEPA) filters with filtering efficiencies of 99.97%, taking into consideration also the Minimum Efficiency Reporting Value (MERV) Parameters (ANSI/ASHRAE 1992, 2012, 2015; ASHRAE 1995; CTI 2011). Also, different species of viruses (Varicella, Rubella, Orthomyxovirus, etc.) can be carried in the air and transferred through the HVAC system but, since their dimensions are often submicron in size, there is no evidence as of now of an effective method to completely eliminate viable particles and, consequently, the majority of pathogenic viruses. Several experimental studies are still in progress to develop filters of greater efficiency, superior to ultralow penetration air (ULPA) filters or for the use in-line of disinfection in HVAC systems (ultraviolet light, chemical vapours chlorine-based, etc.), but there is still no scientific evidence that these methods are effective and, on the contrary, they may represent additional risk for toxic or harmful chemical–physical contamination. In addition to bacteria and viruses, moulds also contribute to contaminate HVAC systems, either because of

poor maintenance and cleaning of the pipelines and filters or slats of anemostats, especially in the presence of building sites both inside and outside the hospitals. In building sites outside the hospital, there may be large earthworks and excavations that produce large emission and diffusion of hyphae. Within hospitals, particular conditions of temperature and humidity can cause mould, especially in the areas of countertops or in the cavities of the walls. Moulds, such as Aspergillus spp., Mucorales/Rhizopus spp. and Scedosporium spp. (and particularly in air filters Penicillium spp., Acremonium spp. and Cladosporium spp.), are called into question, in these cases, and can have serious consequences for immune-compromised cancer and organ- or bone marrow-transplant patients (CDC 2003).

Infection control problems often involve a viral, fungal or bacterial contamination within health facilities. Ventilation air dilutes the viral and bacterial contamination yet, sometimes, it contributes also to the dispersion of fungal hyphae. Theoretically, if the hospital is built and located in a well-ventilated area, the HVAC system air intakes are placed so as to not capture contaminated air, and without any external source of risk for contamination (biological, chemical and physical) outdoor air should be more free of contaminants than the hospital indoor air (in relation to the presence of potentially infected patients, use of chemical and physical substances for the patient's therapy and surfaces disinfection, etc.). Therefore, if the ventilation system is properly planned, designed, installed, maintained and properly kept clean to preserve the correct pressure relations between functional hospital environments and areas, it removes airborne infectious, chemical and physical agents from the hospital environment. In order for an HVAC system to have an optimal operation, to contribute in reducing the risk of infection and contamination and to not be in itself the subject of contamination, it is important that certain parameters be constantly monitored by an "air and water risk management service" and, in case of HVAC failure, the best operating conditions should be immediately restored within the parameters set by the manufacturing company.

Temperature and humidity and air quality can inhibit or promote the growth of—and activate or deactivate–microorganisms. For this reason, technical standards and guidelines set out the principles and criteria to follow so as to determine a range of values for each of the HVAC system operating parameters in different hospital areas, as a measure for the control of infection and chemical or physical exposure as well as for comfort, determining an overall minimum impact on health.

The correct planning and location of the outdoor air intakes and exhaust outlets of an HVAC system should include the following precautionary elements (ASHRAE 1995):

- Outdoor intakes should be located as far as practical, but not less than 9 m from cooling towers, ventilation exhaust outlets from hospital or adjacent buildings, combustion equipment stack exhaust outlets, plumbing vent stacks and medical-surgical vacuum systems and areas that may collect vehicular exhaust and other noxious fumes. Consequently, it is not recommended to install the outdoor air intakes at ground or subground level, but at a minimum of 1.8 m from the ground level and, however, not in the potential direction of air flows or

of toxic emissions. However, exhaust air must not short circuit into the intakes of outdoor air treatment units or fan systems used for smoke control.

- Exhaust outlets should be located a minimum of 3 m above ground level and away from operable windows, occupied areas, doors or other facilities. It is preferable that the exhaust outlets be placed at roof level projecting upwards or horizontally away from outdoor intakes. For this reason, it is always necessary to take into account the proximity of buildings or of other critical structures, the prevailing winds that are present in the area and the speed of the emission flows.

The importance of the air filtration is well emphasized in many technical and legislative regulations or national and international standards, and the removal of particles is a key objective to prevent the transmission of airborne infections. All central ventilation of HVACs systems should be equipped with filters with the appropriate class of filtration, increasing the need for cleaner air in rooms where patients at increased risk of infection (or allergy) are being treated or hospitalized. When only one filter bank is to be expected (e.g. in hospital areas where patients are at lower risk of contracting an airborne infection), it should be located upstream of the air-conditioning system (ASHRAE 1995). Conversely, when two or more filter banks will be present, for the occurrence of patients with a high degree of immunosuppression, they should be located one upstream of the air-conditioning equipment and the others should be downstream of the supply fan, water-reservoir-type humidifiers, any recirculating spray water systems, or other systems that can humidify or pollute the air circulating. In fact, both in the design stage and in the installation every precaution must be taken in order to prevent that the filters might, in some way, become moist, so as to turn into culture media for microorganisms and fungi. Moreover, the HVAC system for the hospital rooms used for the clinical treatment of patients with high susceptibility to infections (leukaemia, burns, bone marrow or organ-transplants, etc.), as well as operating rooms, should be equipped with HEPA filters. The filter system should be designed and installed to permit safe, easy and economically sustainable removal, disposal, cleaning and replacement of polluted or contaminated filters. All filters should be installed in order to prevent leakage between the filter segments and between the filter bank and its supporting frame (ASHRAE 1995). It must be taken into account that any errors in the installation, which leave cracks or tears in the filter, can create sources of serious air contamination downstream of the filter, making the filters ineffective in their function. Electronic equipment, optical and flow sensors, differential pressure gauges, etc., should be installed in the filter system to measure any pressure differences or state of clogging of the filter banks. This precaution could be very useful for both determining the wear time and, therefore, the duration of the filters and the need for their replacement, both for indirectly assessing the state of cleaning of the air downstream of the HVAC system and the need for its cleaning and of the pipes' disinfection.

During construction, openings in ductwork and diffusers should be sealed to prevent intrusion of dust, dirt and hazardous materials, because this contamination is often permanent and provides a medium of growth of infectious agents or

transmission of extraneous materials. Therefore, pre-existing or new filters may rapidly become contaminated by construction dust. As a consequence, it would be appropriate that the ducts that were sealed during construction, once the work is finished, be cleaned by flushing with inert gas and that filters that were exposed to outdoor construction work be quickly replaced with new filters. Gaps in and around filter banks and the presence of dirt, dust and debris upstream of poorly maintained filters have all been implicated in hospital-associated outbreaks of aspergillosis, especially when accompanied by construction activities at the facility (Sarubbi et al. 1982; Pittet et al. 1996; Rao et al. 1996).

Because high-efficiency filters are expensive, the designers of hospital HVAC systems should plan for air-conditioning systems, ducts and filter banks to be easily accessible through appropriate openings, and that the system enables not only an economically sustainable and rapid maintenance, but also a simple management of the cleaning and sanitization procedures of the pipelines, so as to not generate an impact on patient's health. Therefore, it is crucial to take into account during the design and installation of the system all the sources and factors of risk, considering as part of the project (both in the case of a new construction and that of restructuring) also the lifetime of the filters, the maintenance costs and the most appropriate conditions in performing the procedures for the maintenance and cleaning of conducted air diffusion, without negatively interfering with the organization of the health care and the health of patients (Moscato et al. 2013a, b; D'Alessandro et al. 2016) (Fig. 2).

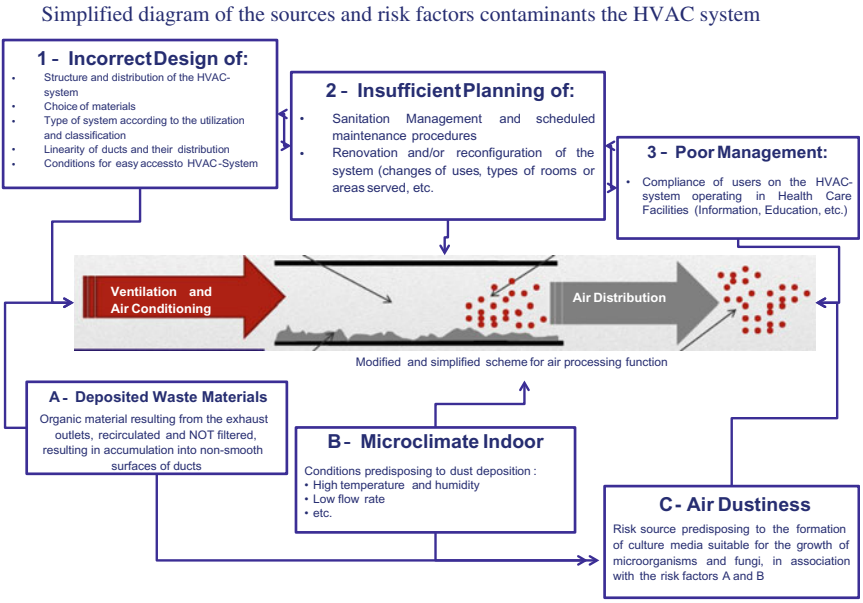

Fig. 2 Simplified diagram of the sources, conditions and risk factors of contamination of the HVAC system

In many healthcare facilities, the normal patient care activities can generate a dispersion of particles in the air that might carry microorganisms and fungi. Because of the dispersal of bacteria resulting from these activities, air-handling systems should provide air movement patterns that minimize the spread of contamination. The opening of doors, changes in temperature and humidity, the uncontrolled movement of staff-workers, patients and visitors can generate undesirable air flows that are difficult to control and which can be accentuated by vertical openings such as elevators, stairs (static or stairs-furniture), light wells or horizontal paths (i.e. service corridors and bridge connections between departments). Although some of these factors are beyond practical control, the effect of others may be minimized by concluding shaft openings in enclosed rooms and by designing and balancing air systems to create positive or negative air pressure, confining the air flow and dispersion of contaminants in certain environments, areas or rooms.

Design of the ventilation HVAC system should as much as possible provide air movement from clean to less clean areas, considering also variable air volume (VAV) systems, both for energy conservation and to reverse any negative pressures into positive and vice versa (in particular when it is necessary to apply restraint to the diffusion of toxic or radioactive pollutants compared to the patient's state of immunodeficiency). The number of air changes may be smaller than the nominal value or standard indicated, when the room is not occupied or is not in activity, if organizational mechanisms of compensation were implemented (reduction in the number of accesses in the room or area, reducing movement of personnel or patients, etc.) or if the number of air changes is re-established whenever the space is occupied and the pressure relationship with the surrounding rooms is maintained when the air changes are reduced. In areas requiring no continuous directional control, ventilation HVAC systems may be shut down when the space is unoccupied and ventilation is not otherwise needed (ASHRAE 1995). This does not apply if the laws, setting environmental parameters albeit variable, determine, as often happens with Italian national and regional laws, that reference values cannot be modified by scientific evidence (in particular, for example, the possibility of reducing the air changes either in the presence of people and activities or in the absence of these in unoccupied rooms), going into conflict also with other national or European directives, such as in relation to energy saving and environmental sustainability.

The constituent elements of a UTA (air treatment unit) are subject to various types of problems. For example, the humidification systems of HVAC can become encrusted and corroded. In winter, the mechanical and filtration HVAC components, dedicated to air humidification, may undergo proliferation of microorganisms in the water and deposits on the nozzles. In summer, the water collection tank condensation may collect microbial flora and airborne spores, forming bacterial fomites. Typically, the range of temperature within which a cooling tower works ($25° \cong 35°$) is ideal for the growth of *Legionella pneumophila*. The supply fan is, also, a reservoir of mineral and organic waste. The air conveyed by the ventilation systems in the pipelines brings with it debris, dust, elements and chemical products

of organic nature and inorganic anthropogenic and natural origin. While humidification systems with poor condition and maintenance have been associated, in the case of US office buildings, with significantly increased upper respiratory symptoms, fatigue, difficulty concentrating, and skin and eye symptoms, and less frequent cleaning of cooling coils and drain pans have been associated with significantly increased eye symptoms and headache, in hospitals the health effects of poor cleaning and maintenance of these systems can be of much greater magnitude, often resulting in a worsening of the patient's condition and can also determine an increase in the risk of the patient's death (Mendell et al. 2008; Moscato et al. 2013a; Laurenti et al. 2013; Ricciardi et al. 2015). Unfortunately, in the healthcare facilities, where the majority of the occupants are not in good health and are susceptible to even small amounts of contaminants or microorganisms present in the air, the importance of a clean intake section and dry air filter of the HVAC system would be essential to draw away dust containing deposited microorganisms, but the execution of mechanical cleaning of the HVAC and pipelines in the hospital, with current technology, may result, to date, in a greater risk of dust release during cleaning, considering the amount of powder which is dispersed during the daily operation of the HVAC system (burst effect) (Hanssen 2004; Moscato et al. 2013a). Therefore, the cleaning operation of the HVAC system and pipelines should be performed on off-air-conditioning systems and rooms or areas without people inside. This is extremely difficult to put in practice in some areas such as emergency departments, operating rooms or ICUs (Intensive Care Units), where the state of occupation of the spaces is continuous every day of the year (unlike other types of HVAC systems and of residential or administrative buildings), unless it is possible to transfer the patients in other areas, suitably dedicated, not only during the cleaning operations, but also for some time after because of the effect of the residual contamination by spores (e.g. of Aspergillus spp.) released in the environment, which may cause effects on susceptible subjects (Moscato et al. 2013b). One should consider the costs, both direct and indirect, related to the reduction of the healthcare activities, since there is a probability of an increase of healthcare-associated infections, paradoxically after maintenance and cleaning of the system, where such activities have not taken due account of the differences characteristics of healthcare structures (health facilities and the presence of susceptible subjects to infections and allergies) as opposed to other environments (Health Quality Ontario 2005). This, of course, is also reflected on the level of skills and training preparation of the technical services that must manage and execute these activities. Therefore, it is possible to structure a risk matrix, depending on the hospital and the patient's susceptibility, which must involve a specific schedule for the management and maintenance of cleanliness and sanitation of HVAC system and ductworks distributed in those areas, fundamentally from the time of design and installation, providing all aspects of life-cycle maintenance, where the facility must be involved. An example of a risk matrix for the susceptibility of the patients as a function of healthcare environments to be subjected to cleaning and sanitization of HVAC systems and the level of maintenance to be planned and executed, is described in Fig. 3 (Moscato et al. 2013a, b; Ricciardi et al. 2015).

Risk Matrix	HVAC-system Management			
At-risk Groups	Maximum Level Filtration , Maintenance and Sanitizing	Medium Level Filtration , Maintenance and Sanitizing	Minimum Level Filtration , Maintenance and Sanitizing	LackHVAC-Systems Management
Group 1 • Hospital social areas, public or communication • Administrative offices • Inpatient areas not occupied (by patients)	Minimum	Medium	Medium	Medium-High
Group 2 • Surgeries and external access areas (except for out-patients from areas 3 or 4) • Admission/discharge areas • Patient areas with patients not pertaining to the level 3 or 4	Minimum	Medium	Medium-High	High
Group 3 • Emergency Unit • Radiology and Nuclear Medicine • Day Surgery and Different areas of the Operating Room • Post Operative Intensive Care or Post Anaesthesia • Laboratories • Echocardiography • Physiotherapy Areas • Neonatology and paediatrics • Geriatrics and long -term care • Internal Medicine and General Surgery	Minimum	Medium-High	Medium-High / High	Very High
Group 4 • ICUs • Operating Theatres • Anaesthesia induction rooms • Oncology departments for outpatients • Transplant Departments (bone marrow and others) and outpatient clinic for outpatients who have received transplants • Dialysis units • Inpatient wards with HIV or immunosuppressed patients • Areas of angiography or hemodynamic and cardiology • Endoscopy Areas • Pharmacy, pharmaceutical preparation and parenteral nutrition • Sterilization Unit • Sterile or clean instruments d eposits	Minimum / Medium-High	Medium-High / High	High	Maximum

Fig. 3 Matrix of the risk level to which the patient is exposed in air-conditioned hospital environments. Relationship between risk groups (for patient areas), and the level of maintenance, filtration and sanitizing of the HVAC system

Therefore, an accurate organizational planning is required, which is not always easy in health facilities even considering several studies which show that, after cleaning of aeraulic ductworks, environments that are downstream are contaminated from days to weeks (sometimes months after the cleaning of pipelines), despite careful sanitation of hospital rooms (CDC 2003). Always bearing in mind that the turning-off of hospital HVAC systems, and in particular surgical wards systems, can result in the stagnation of air/water mixture, especially if not filtered, with the proliferation of microorganisms and their release in the burst at the time of reactivation of the HVAC system. Several studies describe different environmental contamination events. Among them is an episode in which *Acremonium kiliense* was released by an HVAC humidifier during cataract surgery due to reactivation after being turned off for the night (CDC 2003). Airborne particulate matter, dust and biochemical aerosol concentrations are usually higher during the cleaning and sanitization process, although cleaning procedures are generally effective in reducing (but not eliminating) microbial contamination. Thus, inpatients should not stay in hospital areas during the cleaning/sanitization procedures and the cleaning staff should wear protective suits and masks to protect themselves from biochemically-contaminated air (Ahmad et al. 2001). And this considering that while infrequent cleaning of the exhaust ducts has been documented as a cause of

diminishing air pressure control and decrease in the air exchange rates, no data indicate that pipeline cleaning and sanitization, beyond what is recommended for best HVAC system performance, improves significantly indoor air quality or reduces risk of infection, specifically in healthcare facilities (ASHRAE 1999). Therefore, there is still no consistent and valid scientific evidence that dust cleaning, from HVAC system pipelines, has been shown to prevent any health problems and different studies "[…] indicate that airborne particulate levels do not increase as a result of dirty air ducts, nor do they diminish after cleaning or sanitization, presumably because much of the dirt inside air ducts adheres to duct surface and does not enter the conditioned space […]" (US EPA 1997). Thus, despite high efficiencies of contaminant removal within the ducts during cleaning, rate of decreases for different indoor air pollutants varies widely; post-cleaning air pollutant concentrations can be higher than precleaning levels, and so, there is still inadequate scientific evidence useful to show that ducts-cleaning improves airflow and energy saving in HVAC systems, and does not cause impact on health, especially in healthcare settings where patients' health conditions make them at high risk of developing a nosocomial infection. So, if HVAC system in healthcare facilities is properly designed, installed, managed and maintained, it becomes crucial for maintaining the ideal temperature and humidity conditions of patients and staff, improving air quality and reducing the likelihood of infection and of the onset of hospital outbreaks.

Contrary to what one might think, the HVAC system design is often a compromise between the needs of the architect, the civil engineer and of the HVAC engineer, not through a coordinated planning in the initial phase of the project, but with each of them acting in phases which are subsequent to the construction of the building, when the HVAC system installation is already made complex by the work which has already been performed. It appears, therefore, increasingly essential in the future of healthcare facilities that HVAC systems be designed, installed and operated with a multidisciplinary approach that takes into account the specific hygiene needs of healthcare environments.

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Assessment of Indoor Air Quality in Inpatient Wards

Gaetano Settimo, Marco Gola, Veruscka Mannoni, Marco De Felice, Giorgio Padula, Ambra Mele, Barbara Tolino and Stefano Capolongo

Introduction

The Indoor Air Quality (IAQ) is an issue that in recent decades is obtaining great attention both because the dangers due to air pollution exposition in confined environments become more evident and the continuing goal of improving the quality of people's lives (WHO 1984, 1999, 2010; ECA-IAQ 1991). The breakthrough happen at the end of 2010 with the publication for the first time of

G. Settimo · V. Mannoni · M. De Felice · G. Padula
Department of Environment and Health, Istituto Superiore di Sanità,
Viale Regina Elena 299, 00161 Rome, Italy
e-mail: gaetano.settimo@iss.it

V. Mannoni
e-mail: veruscka.mannoni@iss.it

M. De Felice
e-mail: marco.defelice@iss.it

G. Padula
e-mail: giorgio.padula@iss.it

M. Gola (✉) · A. Mele · B. Tolino · S. Capolongo
Department of Architecture, Built Environment and Construction Engineering,
Politecnico di Milano, Via G. Ponzio, 31, 20133 Milan, Italy
e-mail: marco.gola@polimi.it

A. Mele
e-mail: ambramele@gmail.com

B. Tolino
e-mail: barbara.tolino@gmail.com

S. Capolongo
e-mail: stefano.capolongo@polimi.it

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guidelines for indoor air quality for some specific pollutants in confined environments by WHO (Settimo 2012, 2015; Settimo and D'Alessandro 2014).

Verifying IAQ in confined spaces of public and private companies, such as offices, schools, gyms, manufacturing environments, etc., is a strategic preventive action to protect and improve the health and safety conditions of workers. The environment in which people live and work can be the cause of diseases' insurgence linked to indoor environmental factors and classified in the group well-known as Building-Related Illness (BRI) (WHO 1999; Settimo 2012); but it can also be due to a syndrome that affects an important percentage of occupants, with nonspecific symptoms but repetitive, not attributable to a specific agent-recognized as the Sick Building Syndrome (SBS).

If IAQ is reputed important in workplaces and housing, it is essential that its supervision within a healthcare facility, considered as a complex construction for its several functions and the multitude of users who interact within it (Capolongo 2016), must be on the agenda. In fact, ensuring a good IAQ in hospitals is fundamental because there is the most vulnerable category of the population for their health conditions; although the assessment of IAQ results arduous.

Currently, there are some research studies that are reporting a growing number of data and analysis that allow to know all the possible indoor levels and the development of management procedures, such as choices of furniture and finishing materials, products for cleaning and disinfection, management and maintenance of *air handling units* (AHUs) and heating, ventilating, and air-conditioning (HVAC) *systems*, activities carried out within the room, etc.) in order to improve the healing environments and health of medical and technical staffs, patients, ambulatory users and visitors (Capolongo et al. 2016; Boccia et al. 2015).

Although, as emerged from the scientific literature, especially in Italy, the indoor air quality's issues in hospitals still has little attention. Currently, the only environments analyzed are spaces that are more at risk of disease as the emergency room, operating rooms and delivery rooms.

Often for the analysis the references provided for industrial hygiene are considered, such as the industrial occupational exposure limit values (VLEP) in Legislative Decree No. 81 (Italia 2008) or threshold limit value (TLV) by American Conference of Governmental Industrial Hygienists (ACGIH) (Settimo 2015). However, this approach is improper because in inpatient rooms there are vulnerable persons; this means that the current references used are developed for professional workers in good conditions, undergoing specific surveillance controls typically using personal protection devices.

In several countries, in recent years, it has significantly increased awareness in indoor issues, creating specific working groups that have developed guidelines and/or reference values for air quality in indoor environments (Settimo 2015; Settimo and D'Alessandro 2014). Thus until today, the more information about guidelines and reference values in indoor environments, to be used for a first comparison, are those that can be taken by the scientific literature or some specific hospital experiences, or by some European countries' legislations or, once again, by

analogy to other standards, such as those relating to ambient air (Settimo 2012, 2015).

In any case, nowadays, there are several institutions that are increasing knowledge on indoor air quality issues and to define priorities and objectives to be achieved. Currently Istituto Superiore di Sanità (Italian National Institute of Health) is developing some technical and scientific documents of activities at national level taking into account the recommendations already prepared by WHO (WHO 2006, 2010).

Starting from these considerations, Istituto Superiore di Sanità and Politecnico di Milano have launched a research work for the evaluation and detection of air quality in inpatients rooms, examining formaldehyde and volatile organic compounds (VOCs) and the relative influence of thermo-hygrometric, ventilation and concentration of pollutants' parameters.

The paper reports the results of an analysis of indoor air quality on two hospitals' inpatient rooms, in an urban area in Northern Italy. The first hospital is newly built about 20 years ago, while the second one was built 80 years, but recently, in 2015, it has been renovated. One of them is a site in close proximity to an agricultural area, while the other hospital in a site with heavily trafficked roads. Some inpatient rooms were subjected to detecting campaigns of specific volatile organic compounds (VOCs), in order to estimate indoor air levels. Other possible indoor causes are essentially related to cleaning and sanitizing processes, building materials and furnishings, the mechanical ventilation system, the activities carried out, etc. (D'Alessandro et al. 2016).

The report presents the first results obtained during the detecting campaigns, still ongoing, collected in winter 2015–2016.

Methodology

For taking a survey of indoor air quality within healing environments is required a strong cooperation with the chief medical officer and security manager, with which have inspections and identify inpatient rooms for the detecting campaign (Capolongo 2016).

In addition for carrying out the analysis, it is necessary to collect all relevant information concerning the healthcare facility (dimensional data, hospital layout, engineering plants' system, maintenance and cleaning activities, cleaning products, etc.), the activities inside the room analyzed (cleaning activities, presence and number of visitors, the absence or presence of patient/s during the day, etc.), as well as specific information about instrumentation adopted for the survey (formaldehyde, VOCs, relative humidity, temperature, carbon monoxide and carbon dioxide, air speed, etc.) (Cavagliato et al. 2015).

Structure's Dimensional Data, Organizational, Management and Maintenance Aspects

For the evaluations to be carried out, it is essential to obtain several information about the healthcare facility and its healthcare processes. Information about its historical and recent evolution are useful references to better understand construction materials, as well as Technical data sheets and supplies, safety data sheets, etc., easy accessible for recent built interventions.

In particular, for each structure the following data are required:

- plans and sections drawings of the area surveyed;
- technical data of mechanical equipment within the room (type of system, changes per hour, average temperature of the rooms, etc.);
- the finishing materials and furniture of the room (data sheets for each material used);
- chemical risk assessment, prepared by the security manager;
- products used for cleaning and disinfecting, with their technical data sheets (Boccia et al. 2015).

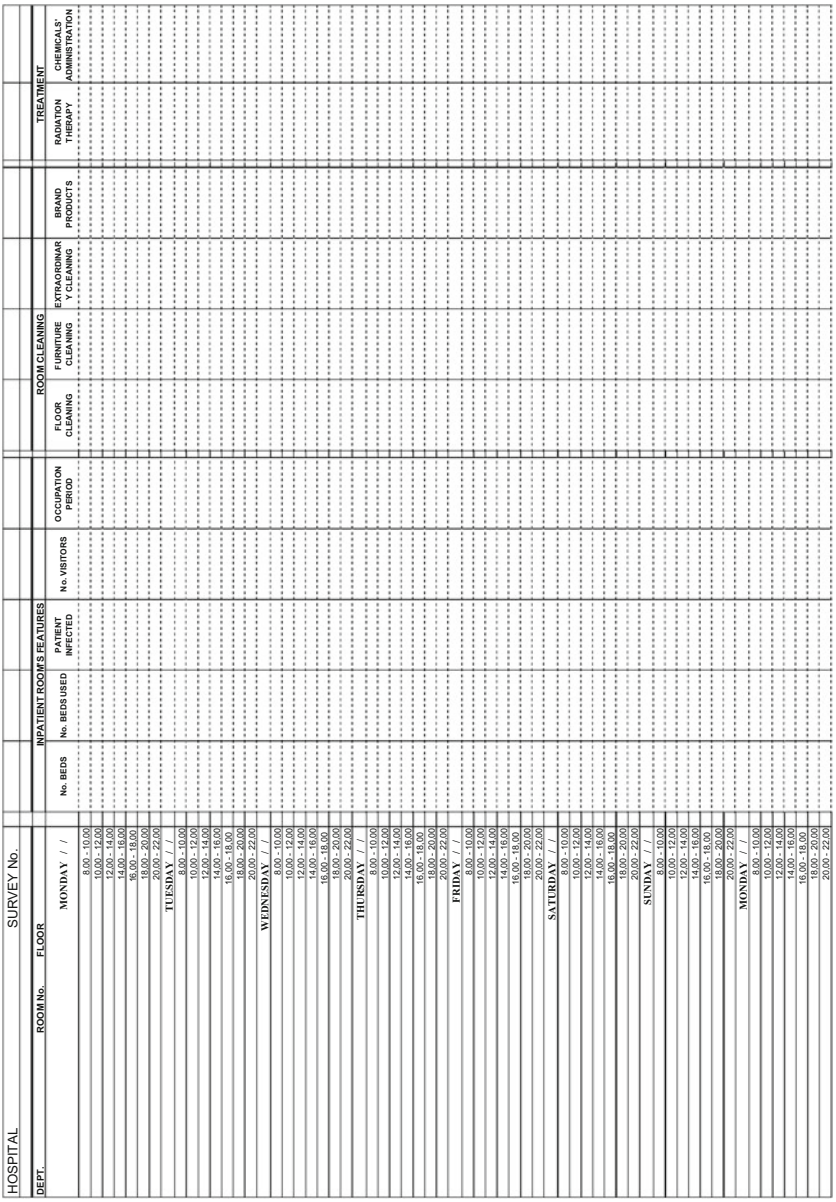
Activity Log

To taking note daily of all the events, the charge nurse of the hospital ward surveyed has to fill in an activity log day-to-day of the inpatient room, such as specific features and cleaning of the room, specific treatments to which patients were subjects, presence of visitors, etc. As emerged in Fig. 1, it is requested that table is filled in its entirety, specifying different times of activities.

Survey Setting and Technical Instruments to Be Employed

In the light of the State of the Art, it is considered to be of primary importance to proceed a detecting campaign of selected VOCs, obtaining indications on concentration levels of acetone, benzene, chloroform, dichloromethane, ethyl benzene, o,m,p-xylene, styrene, tetrachlorethylene, trichlorethylene, formaldehyde and acetaldehyde.

The choice of the operating strategies (pollutants' type, detection and analytical methodologies, instrumentation, etc.) has been made considering the specific indoor air standards ISO 16000 (ISO 2004a, b; 2007; Settimo 2012; Settimo and D'Alessandro 2014). In addition, the methodology considers some guidelines drawn up by the National Working Group on Indoor Air of the Italian National Health Institute (ISS).



HOSPITAL SURVEY No.

DEPT. ROOM No. FLOOR

	INPATIENT ROOM'S FEATURES					ROOM CLEANING				TREATMENT	
	No. BEDS	No. BEDS USED	PATIENT INFECTED	No. VISITORS	OCCUPATION PERIOD	FLOOR CLEANING	FURNITURE CLEANING	EXTRAORDINARY CLEANING	BRAND PRODUCTS	RADIATION THERAPY	CHEMICALS' ADMINISTRATION
MONDAY / /											
8.00 – 10.00											
10.00 – 12.00											
12.00 – 14.00											
14.00 – 16.00											
16.00 – 18.00											
18.00 – 20.00											
20.00 – 22.00											
TUESDAY / /											
8.00 – 10.00											
10.00 – 12.00											
12.00 – 14.00											
14.00 – 16.00											
16.00 – 18.00											
18.00 – 20.00											
20.00 – 22.00											
WEDNESDAY / /											
8.00 – 10.00											
10.00 – 12.00											
12.00 – 14.00											
14.00 – 16.00											
16.00 – 18.00											
18.00 – 20.00											
20.00 – 22.00											
THURSDAY / /											
8.00 – 10.00											
10.00 – 12.00											
12.00 – 14.00											
14.00 – 16.00											
16.00 – 18.00											
18.00 – 20.00											
20.00 – 22.00											
FRIDAY / /											
8.00 – 10.00											
10.00 – 12.00											
12.00 – 14.00											
14.00 – 16.00											
16.00 – 18.00											
18.00 – 20.00											
20.00 – 22.00											
SATURDAY / /											
8.00 – 10.00											
10.00 – 12.00											
12.00 – 14.00											
14.00 – 16.00											
16.00 – 18.00											
18.00 – 20.00											
20.00 – 22.00											
SUNDAY / /											
8.00 – 10.00											
10.00 – 12.00											
12.00 – 14.00											
14.00 – 16.00											
16.00 – 18.00											
18.00 – 20.00											
20.00 – 22.00											
MONDAY / /											
8.00 – 10.00											
10.00 – 12.00											
12.00 – 14.00											
14.00 – 16.00											
16.00 – 18.00											
18.00 – 20.00											
20.00 – 22.00											

Fig. 1 Inpatient room's activity log to be filled in by the charge nurse

For the survey, passive samplers (radiello® model, one specifically for formaldehyde and acetaldehyde, and another for VOCs) are used, whose position must be done when the room is empty and sanitized, at a distance between 1 and 2 m from the wall and at a height of about 1.2 m from the floor (ISO 2004a, b,

HOSPITAL SURVEY No.

DEPT.	ROOM No.	FLOOR	diffusive body code	cartridge code	survey code	date	time	survey detector
1. INDOOR								
SAMPLER POSITION								
height from the floor								
distance from the wall								
		FORMALDEHYDE placement						
		pick up						
		VOCs placement						
		pick up						
2. OUTDOOR								
SAMPLER POSITION								
height from the floor								
distance from the wall								
		FORMALDEHYDE placement						
		pick up						
		VOCs placement						
		pick up						

Fig. 2 Survey log to be filled in by the survey's detector

2007; ECA-IAQ 1991, 1994; Fuselli et al. 2013), taking account naturally also of the activities that must perform by the medical staff.

It is necessary to introduce a microclimatic control unit for measuring the following parameters: CO, CO_2, temperature, relative humidity and air velocity. To understand the indoor pollution values, it must be also provided an outdoor location nearest the room analyzed (Nyhan et al. 2016; Vittori 2011), taking into account the façade and the fixing points available for the positioning of the samplers (ISO 2004a, b, 2007; Fuselli et al. 2013).

The passive samplers consist of a chemi-adsorbent cartridge for formaldehyde and acetaldehyde, with a stainless steel cylindrical grid (Ø 4.8 mm), and for other VOCs (Ø 5.9 mm). The cartridge for formaldehyde and acetaldehyde contains florisil, coated with 2,4 DNPH (2,4-dinitrophenylhydrazine), on the contrary, the VOCs' cartridge is made in activated carbon. The adsorbent cartridge is contained in the cylindrical body made with microporous polyethylene synthesized, which is mounted on a polycarbonate support.

Survey Timetable and Processing Data

The evaluation should be carried out during a year, divided into summer and winter session. The duration of each survey is 7 days, which can be reduced to 5 days in the case of specific requirements agreed with the chief medical officer. This duration allows to evaluate a long period of time and take into account possible changes due to health activities, seasonal microclimate, the operation's variability of mechanical ventilation system, etc. (ISO 2004a, b, 2007; ECA-IAQ 1991, 1994; Fuselli et al. 2013). It is expected that some sampling can be canceled for mistakes by medical staff.

The data processing is carried out by ISS in Rome. The samples should be processed with the Survey log (Fig. 2), filled out by a survey's detector.

The samples, after extraction with solvent, are subjected to the GC-MS and HPLC analysis (ISO 2004a, b, 2007; ECA-IAQ 1991, 1994; Fuselli et al. 2013).

Results

The inpatient room of the first hospital is single (20 m^2, height 3 mtm) and it is localized at the first floor. It has air conditioning system equipped with G4 F7 filters (80–90%) and F9 (efficiency >95%) to all constant fresh air. The walls and floors are coated in PVC; instead frames are made of aluminum and double glazing. The standard furnishings are made of solid wood (wardrobe, bedside table and desk) or steel and PVC (bed, curtain, IV stand, lamps), or covered with eco-leather (bed, sofa, chairs). The availability of the medical staff permits to do the sampling on seven days. The passive samplers have been positioned respectively, internally,

hanging from the wall brackets for TV and, externally, at the ground floor, in correspondence of a permanent scaffolding.

The other room (the second case study) is double (17 m^2, height 3.4 m) and it is at first floor. The inpatient room is, currently, not yet provided with air conditioning, whereby, the air exchange takes place opening windows for about 15 min per day. Furthermore, it is heated by cast iron radiators positioned under the window. The window frames are in wood and the standard furnishings are made of PVC (wardrobe, bedside table and shelf-desk) and steel and PVC (bed, chairs, IV stands, lamp). The availability of chief medical officer permits to do the sampling only on five days. The passive samplers have been located respectively, internally, hanging from a movable IV stand and, externally, on a terrace at the second floor of a building in front of the inpatient room. This last case study recently (October 2015) was renovated: the walls have been painted with a water-based paint for indoor photocatalytic type, but, studying the technical data sheet, it emerged that the product is suitable for workspaces with high humidity, such cheese factories and food industries.

Discussion

From the analysis, it is clear that VOCs sources in the inpatient rooms are several and related mainly to finishing materials and furniture (furniture, floors, walls, etc.), products used for cleaning and disinfection for floors and furniture, the frequency of air conditioning's maintenance and the forced ventilation system. In addition, it is necessary to consider the influence of human activities, and some other aspects related to their permanence (products for personal care, schedule visits, etc.).

Typically, VOCs' levels of contamination in indoor environments are influenced by microclimatic conditions (temperature, relative humidity, airspeed) that affect differently the pollutant emission.

The analysis allows to outline a first picture regarding the situation on indoor air quality on VOCs' influence in hospital wards.

A first data evaluation can be done comparing the values of Guidelines for indoor air quality by WHO (WHO 2010) and the Legislative Decree 155/2010 amended (Italia 2010), which adopted EU directive 2008/50/CE (Europe 2008). The concentrations of VOCs monitored, in those monitoring campaigns, although on short period, fully respect WHO reference values.

In addition, the data collection can be compared with WHO guidelines for indoor air quality or with some legislation references of some European countries or, even more, proposals made by some working groups specifically set up by several countries.

In this Legislative decree 155/2010 are established the limit values for human health protection from benzene. The limit value of the average year on year has been set at 5 $\mu g/m^3$ (Settimo 2015).

In fact, the indoor levels of benzene present, during the preliminary investigations, concentrations that do not differ significantly between the two case studies, with values between 1.6 and 6.3 μg/m^3. The concentration values related to the first hospital room are lower than those related to the other one; this phenomenon can be attributed to the different characteristics of the sites where healthcare facilities are localized and the detection period (cold season) (Oppio et al. 2016).

Instead, for formaldehyde into ambient air, although it is not yet normed at European level, the concentration values measured ranged between 2.8 and 16 μg/m^3, weekly lower than both the WHO guidelines (100 μg/m^3 although reported 30 min) and those present in the specific legislation of several European countries (e.g. France) (Settimo and D'Alessandro 2014; Settimo 2015).

For other VOCs, although the monitoring campaign is based on a short period, the concentration values were lower than the WHO guideline values and those provided in the legislation of several European countries (Settimo and D'Alessandro 2014; Settimo 2015).

The current results have confirmed that the knowledge on IAQ and its evolution can be useful in order to improve continuously the air quality in healing environments (e.g. special attention in the drafting of renovation specifications, choice specific materials, or maintenance of UTA, operating procedures for cleaning, maintenance and disinfection, etc.), where there stay the most vulnerable categories of the population.

However, it is important to remember that the only reference to guidelines' values or taken by shared scientific knowledge, in the case of IAQ data feedback, is less effective in the management of the monitoring and in the decision making.

Conclusions

In the light of the preliminary investigation, it is considered appropriate to draw up a monitoring strategy that takes into account the constraints of use and delivery of health services on a continuous cycle. In order to avoid unproductive and unrealistic measurements, samplings must be carried out by competent professionals in the field of IAQ.

The present results confirm that the knowledge in indoor air quality's issues can be useful in order to improve continuously these hospital environments where persist the most vulnerable users. It is essential to pay particular attention to the renovation program specifications, the choice of construction materials, periodic maintenances of HVAC, the selection of cleaning and disinfection products compatible with the materials' features and the correct procedures operational cleaning and disinfection, etc.

Some considerations on the data can be done starting from the comparison with WHO guidelines and the Legislative Decree 155/2010 (which considers the Directive 2008/50/EC and some legislative references of several European countries. The current values of VOCs respect the WHO guidelines. In addition, the

levels of benzene concentrations do not differ significantly among the inpatient's rooms considered, with mean values between 2.8 and 4.8 μg/m^3. In general, the concentration values related to the healthcare facilities are greatly influenced by their location in the urban context, the daily air exchange by HVAC or manual window openings and the tobacco smoke by workers and patients.

On the contrary, the concentration values formaldehyde, not already normed at European context, present a range between 2.8 and 16 μg/m^3, minor that the values already provided in France for kindergartens and nursery schools. For the analysis, it was not possible to refer the WHO value of 100 μg/m^3 because it is referred to 30 minutes. The acetaldehyde's concentration values are lower than the French guide values processed by ANSES (French Agency for Food, Environmental and Occupational Health & Safety) about 160 μg/m^3 for co-exposure to aldehydes.

For the other VOCs, the concentration values are minor than WHO values and to those provided for in the legislation of several European countries (Settimo 2011, 2012, 2015).

In this regard, healthcare facilities must teach to medical staff the importance of this issue, also with the development of behavioral protocols and use of cleaning and disinfection products that workers must comply. The analysis of international case studies has identified that IAQ is rarely considered as a design requirement in architecture for health. This is the reason why it is important to invest in this direction for providing more and healthier environments (Gray et al. 2012).

The IAQ assessment in hospital environments must be strategic in the management and control of the spaces where users work, live, stay, etc.

It is evident that the design making, ranging from the proper choice of hospital construction site, to building materials and furnishings, to cleaning and maintenance activities must be carried out on the basis of research scientific and data (Buffoli et al. 2014; Guenther and Vittori 2014). It is further necessary that the design team is made up of various professionals in order to ensure a multidisciplinary project and synergy in all the aspects.

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Perspectives of Air Quality Control in Healthcare Facilities: Conclusions

Gaetano Maria Fara
G. M. Fara (Corresponding Author)
Department of Public Health and Infectious Diseases
Sapienza Università di Roma, Piazzale Aldo Moro, 5, 00185 Rome, Italy
e-mail: gaetanomaria.fara@uniroma1.it

Today's trend to drastically reduce the length of stay of patients in hospitals is associated with the intent not only to lower the costs of hospitalization, but also to avoid the consequences on people's health of too a long permanence in the wards. Of course we are far from the risk situations considered by Semmelweis in the XIX Century, but we know that an unnecessary stay can favour the appearance of a HealthCare Associated Infection (HCAI).

In general, considering that patients are to be classified—in a way or another—*fragile individuals*, they are exposed to the consequences of different risk factors much more than every other person—like doctors, nurses and technicians—spending her/his time within the healthcare facilities.

Apart the risks deriving from errors in the diagnosis, therapy and assistance, the environment of healthcare facilities can be responsible of a series of consequences, the best known of which—but not the only ones—are HCAIs (Signorelli and Capolongo 2017).

Within the general environmental aspects of healthcare facilities, a paramount importance is assumed by the indoor air, which can become a vehicle of respiratory risks—chemical, physical and biological—but can be of damage also when its characteristics of temperature, humidity, ventilation and particulate content are not at their best, therefore representing from a simple factor of discomfort up to a factor of frank damage to the people under treatment.

Considering also the fact that the italian legislation has not yet dedicated the desirable attention to the quality of indoor air of healthcare facilities, we are devoid of modern regulations and are obliged to resort to international sources or to adapt to our needs, by analogy, rules prepared for other, more generic purposes, e.g. health protection from airborne risks of factory workers. Considering all that, a

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multicentric and multiprofessional group of italian researchers has agreed to go deep into the problem and to publish the results of their research and scientific elaboration in the present volume, which—it is their hope—will hopefully be a stimulus for the enactment of national rules.

As Capolongo et al. (2017) stated, the goal of the present volume is to describe the complexity of the air quality control in the different health facilities, and to show how the problems of providing air of good quality can be solved through interventions on projects, building materials, construction, equipment, maintenance and management.

My opinion is that such a goal has been reached. The eleven chapters of this book illustrate the state of the art of air quality control in healthcare facilities, and I will try, in the following few pages, to highlight the different achievements of the team of Authors, belonging to Istituto Superiore di Sanità or to a number of universities, most of them active in working groups of the Italian Society of Hygiene and Preventive Medicine.

As Settimo and Capolongo (2017) illustrated, to govern the complex problem of air pollution in healthcare facilities, simple rules, emerging from evidence based scientific experience, should be adopted.

Considering that norms on indoor air pollution in several EC member states are still absent, scientific and regulatory work are in progress in many states and at international level, as well illustrated by Gola et al. (2017). It is important and necessary to proceed soon to a harmonization, as suggested by the European Regulatory Committee (CEN) and the International Organization for Standardization (ISO), which have provided a set of specific instructions on standard operating procedures for air quality monitoring. The European Union (EU), within the European Collaborative Action (ECA), has carried out a multidisciplinary collaboration among experts producing a collection of 27 specific papers, published between 1988 and 2012.

Back to 2010, WHO has developed a Guide to Prevention and Good Practice for indoor air quality in healthcare facilities, identifying several dangerous chemicals substances (Settimo and Capolongo 2017). The guidelines specified some values for indoor air quality and provided a scientific reference for legally enforceable standards in all world's countries, suggesting also public health professionals involved in the prevention of environmental exposures' health risks, as well as specialists and authorities to be involved in design, renovation and maintenance of buildings and decision making for indoor materials and products.

As underlined by many of the Authors of this book, differently from other Countries which, inspired also by the WHO standards, gave themselves a modern ad hoc legislation, Italy never adopted a legislation regulating physical, chemical and biological indoor air contamination in healthcare facilities: only between 2005 and 2009 the National Agency for job's prevention and security (ISPESL) wrote ad hoc documents limited to three specific hospital environments (surgery, obstetrics and emergency) (see Settimo and Capolongo 2017), but such documents did not provide concentration limit values, therefore it has been necessary to refer to the

Legislative Decree (LgsD) 81/2008 as a reference text, although it is generic for all kinds of workplaces.

Therefore, Settimo and Capolongo (2017), after an excursus on the different risk factors and their expected effects on patients and personnel, indicate in details how to usefully interpret the rules of LgsD 81/2008 applying them to the situation of healthcare facilities and, further, how to effectively contrast such risk factors with interventions including the planning of spaces (building or adaptation), the use of materials, the right treatment plants and their management and maintenance.

Gola et al. (2017) consider in details one of the steps very critical in order to correctly perform the procedures of risk assessment and of evaluation of the results of the different interventions: the *monitoring of the Indoor Air Quality* (IAQ). This because the indoor air of healthcare facilities not only has to protect the different kinds of people inside from the offense of all possible air contaminants; but we should never forget that quite a few people inside such facilities are deeply sick, some of them with respiratory diseases (e.g. asthma) and others are immunosuppressed, and therefore very sensitive to HCAIs, part of which is transmitted by air and aerosols. The merit of this paper is to offer the reader a detailed series of procedures for IAQ monitoring in healthcare facilities performed internationally, from which we could be inspired for improving our personal experiences of IAQ.

D'Alessandro and Fara (2017), Bonadonna et al. (2017) and Montagna et al. (2017) papers are all interested in different aspects of infectious risk in healthcare facilities. The paper of D'Alessandro and Fara (2017) is devoted to airborne infections, of which it illustrates the association between infective dose and the other virulence factors. After the outbreaks of SARS in 2002–2003, the concerns about an expected avian influenza (H5N1) pandemic and the recent outbreak of Ebola virus disease, the airborne infections have attracted more attention, following a long period in which their role may have been underestimated, due to the difficulty of culturing many airborne organisms and the complexities of assessing the role played by such pathogens in the contamination of environmental surfaces and subsequent contact transmission.

Effective control measure used for the prevention of airborne pathogens transmission are described, focusing mainly on risk assessment and infection control. In order to avoid infections caused by airborne microorganisms it is very important to maintain protective barriers that control the microbiological quality of the air. For aerosolized waterborne pathogens, faucets are easily accessible for preventive measures, and the installation of single-use filters on hospital water outlets appears to be an effective concept to reduce water-to-patient transmissions of nosocomial pathogens.

Some conclusions by D'Alessandro and Fara (2017) are of general interest. One is that in order to prevent HCAIs, two kinds of expertise are necessary, (1) knowledge of traditional infection control and (2) knowledge of human behaviors, to help healthcare workers employ infection control science effectively. Actually, the effectiveness of preventive measures is related to the availability of appropriate periodic maintenance programs to assure the safe ventilation of indoor air, but also the strict compliance with the procedures by the staff. Therefore, it is of

paramount importance to increase healthcare workers' awareness of the risks associated with incorrect behaviors and to improve their training, because, independently from the technology available, the human behavior is crucial to ensure indoor air quality and safety in healthcare setting.

Bonadonna et al. (2017), the second paper devoted to microbiological risk, completes the other aspects of HCAI with other types of transmission, and illustrates the best strategies of disinfection.

The definition of the role that the environment has on the acquisition of hospital infections is highlighted by the need for multiple strategies to control the dissemination of pathogenic microorganisms and the adoption of prevention measures.

The clarification of the role that surfaces have in the spread of infections could provide support to increase adherence to control measures. Improving and intensifying the cleaning routine may reduce the dissemination of pathogens. More attention should be given to the adequacy of the frequency and specific care when cleaning surfaces, because removing dirt helps to reduce biofilms. The spread of pathogens could be prevented by using engineering and environment control strategies. Thus, in addition to cleaning and disinfection standard procedures, the maintaining of appropriate hygienic targets may be obtained by employment of durable antimicrobial materials, such as copper and copper alloys (brasses and bronzes), especially for high-touch surfaces.

Inspired by microbial biocide multi-resistance issues, in recent years new experimental sanitation procedures, based on the use of probiotic products, have been proposed. This technique, defined as bio-stabilisation and based on the principle of competitive microbial exclusion, does not imply a biocidal action. Surfaces-sanitizing probiotic products, containing vegetative and spore forms of *Bacillus* spp, in association with good hygienic practices, are claimed to provide 80–90% reduction of pathogenic agents and more than 60% reduction of infection events. Further research is necessary to define the possible role of such procedures in the routine of sanitation.

Montagna et al. (2017), the third paper treating microbiological aspects, is dedicated to *Legionella pneumophila*, a microorganism of strict environmental origin, which is not transmitted by humans, but has a critical role in the HCAI pathology. Since 2000, some international and national documents related to the control and prevention of Legionnaires' disease have been issued, providing for the sampling of different environmental matrices but not air. To date, the control on water mains is preferred; however, air sampling could be a useful tool for exposure evaluation. To sample biological particles in the air active and passive methods can be used. Several studies have compared the values of microbial counts obtained with active and passive sampling, with discordant results. Based on this scientific background and on the experience about *Legionella* spp. contamination and air microbial sampling in healthcare environments, the Italian Study Group on hospital hygiene (GISIO) of the Italian Society of Hygiene, Preventive Medicine, and Public Health (SItI), in collaboration with the Italian Association of Aerobiology (AIA), promoted two multicenter studies focused on identifying a standardized sampling

protocol to detect airborne pollution coming from water sources contaminated with *Legionella* spp.

The aim of the first study was to compare active and passive sampling methods (SAS sampler and settle plates) in detecting air *Legionella* contamination. Regarding active sampling method on liquid substrate by Coriolis®μ sampler, all 11 health care facilities enrolled were negative by cultural method, but 8 out of 11 resulted positive by molecular investigations. The data suggest that for *Legionella* spp. air detection cannot replace water sampling, but may provide useful support for an adequate risk assessment, especially if associated with molecular investigations.

Oberti (2017) open the second series of three homogeneous papers, devoted to the "shells" of healthcare activity, which means building materials, air treatment plants (Joppolo and Romano 2017) and their management and maintenance (Moscato et al. 2017).

According to Oberti (2017), the most important pollutants emitted from building products, that arouse great concerns, are volatile organic compounds (VOCs), such as formaldehyde, acetaldehyde, naphthalene, toluene, xylene, isocyanates and the semi-volatile organic compounds (SVOCs), such as phthalates and halogenated flame retardants. VOC-type chemicals are used as feedstocks for some plastics and utilized in binders and other resins for products such as composite wood or insulation, in paints, coatings and adhesives, and treatments to guarantee water resistance or to enhance stain repellence. Building materials finishes and furniture containing VOCs include resilient flooring, carpet, wall covering, fabrics, furniture, ceiling tiles, composite wood products, insulation, paints and coatings, adhesives, stains, sealants and varnishes.

The health effects influenced by exposure to indoor pollutants affect patients, staff and visitors. However these effects indent not only building occupants, but also the broader community, because some building products used outside can release contaminants, such as fibres and particulates, contributing to smog formation.

On the contrary, building materials to be preferred, and some of which are already on the market, are characterized by recyclability, origin from renewable resources, minimum waste, local production (zero miles), low embodied energy, low human and environmental impact, and durability.

Joppolo and Romano (2017) are entirely devoted to the problem of air treatment plants, their project, their sizing, the choice of different technical solution according with the situation, their construction and monitoring. Particular interest is devoted to the mechanisms of filtration to get rid of all kind of contaminants, both gaseous and particulate. From this important paper we can conclude that most of technical problems are solved, provided the choice of the plant and its sizing is reasonably done according to the real needs.

Moscato et al. (2017) paper, dedicated to the management and maintenance of the HVAC-system (Heating, Ventilating and Air Conditioning), underline that good management is only possible if plants are correctly realized and of the due size; and also that plants planned for healthy people are not necessarily good for healthcare facilities, which have different, more strict requirements.

The attention to a risk matrix to evaluate and better manage the HVAC-systems, also allows to answer the questions relating to the need to clean or not the air conditioning systems in healthcare facilities, with the risk of spreading microorganisms and chemical particles, instead of reducing it and protect the health of patients.

In conclusion, I hope that the present book will be of some interest for all those involved in the field of planning, building, equipping, furnishing, managing and maintaining healthcare facilities, and will provide them with a modern insight to all the related problems.

As the final contribution, Settimo et al. (2017) underline that ensuring a good IAQ in healthcare facilities is fundamental, because there is housed the most vulnerable section of the population due to her health conditions; they report the first data from a large investigation under way in collaboration between the Politecnico di Milano and the Istituto Superiore di Sanità in Rome, in order to carify the relationship between the physical characteristics of the indoor air in the wards and the level of pollution.

In conclusion, I hope that the present book will be of some interest for all those involved in the field of planning, building, equipping, furnishing, managing and maintaining healthcare facilities, and will provide them with a modern insight to all the related problems.

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