BURAK OZGUR
EDWARD BENZEL
STEVEN GARFIN
EDITORS

Minimally Invasive Spine Surgery

A Practical Guide to Anatomy and Techniques

Springer

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Editors
Burak Ozgur
Director of Minimally Invasive
Spine Surgery
Assistant Professor of Neurosurgery
Department of Neurosurgery
Cedars-Sinai Medical Center
Los Angeles, CA, USA

Edward Benzel
Chairman
Department of Neurosurgery
Cleveland Clinic Spine Institute
Cleveland, OH, USA

Steven Garfin
Professor and Chair
Department of Orthopaedic Surgery
University of California-San Diego
USCD Medical Center
San Diego, CA USA

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I dedicate this book to the support and guidance of my parents, the patience and trust of my professors, teachers, and patients, and certainly to the boundless love, compassion, and encouragement of my wife, Iman, and kids, Omar, Ali, and Hala.

Burak M. Ozgur

I dedicate this book to my wife, Mary. She perpetually provides advice, guidance and friendship. Her unending support is the source of my strength.

Edward C. Benzel

I dedicate this book to my mentors, colleagues, and trainees, who helped me (taught, inspired, and tolerated me) treat patients and teach others.

Steven R. Garfin

Foreword

Unlike any other surgical specialty, spine surgery has evolved rapidly over the past three decades. I have been fortunate to observe this evolution over the past 40 years from the time I started my internship. At that time spine surgery was not a favorite rotation for the house staff and used to take the back seat to all other, more interesting orthopedic procedures. Diagnostic knee arthroscopy was just being introduced, and that was all we knew of the concept of less invasive surgery. During my training as a resident and, later, as a fellow in spine surgery, the focus was on fusion techniques, especially for spinal fractures and deformities. Although many principles of spine care have remained the same over the years, methods and surgical techniques have changed dramatically, as evident in minimally invasive spine surgery (MISS). Most of these techniques have withstood the test of time, though some did not, but all have contributed to our understanding and knowledge of spine surgery.

MISS has been among the latest advances in spine care, leaving a great impact on how we will treat future patients with spinal disorders. Although other specialties have enjoyed applying these methods of treatment for some time, progress in MISS slowly evolved. It started with the treatment of disc disease and now includes fusions, motion preservation techniques, and even spinal reconstruction. Considering the progress made over the past 40 years, I believe that these techniques will continue to evolve and improve over time.

Education plays a great role for progress in any field, in particular in a field as new and demanding as MISS. Today, increased knowledge and understanding about principles and treatment outcomes along with advanced technology allow us to manage more effectively the many conditions of the spine. Indeed, we could not have even dreamed of this a decade ago. However, the education in MISS should emphasize principles first. We should not forget that patient selection should occur on the basis of surgical indication rather than on the available techniques, even if they are less invasive.

The editors of this publication have successfully assembled the current state of knowledge in MISS by many leaders in this field, covering a wide variety of conditions in spine surgery and including both principles and techniques. Indications are clearly outlined and techniques discussed in a cogent and concise manner. As spine surgery becomes one specialized field, there is no doubt that this important book will serve as a valuable resource to both neurological and orthopedic spine surgeons and their trainees. Certainly, as advances continue to be made in our field, this text will serve as a basis for further innovations.

La Jolla, California — Behrooz A. Akbarnia

Foreword

In the last 20 years, spinal surgery has changed tremendously. Progress has included advanced instrumentation, the application of imaging techniques both in and out of the operating room, and improved understanding of biomechanics. Minimally invasive spine surgery, which is becoming a subspecialty in the field of spine surgery, has grown explosively in the last decade.

Minimally invasive spine surgery offers the benefits of decreased postoperative pain and disruption of normal anatomy, and the latter leads to shorter hospital stays. Theoretically, all of these will also decrease the expense of care, but this point has yet to be documented. As with most new techniques, a learning curve is associated with mastering minimally invasive spine surgery. In fact, for procedures such as thoracoscopic approaches to the spine, the learning curve is quite steep. Proficiency requires intensive courses, if not fellowships, to acquire the necessary surgical expertise to perform these elegant yet at times complex procedures. The editors of this book have assembled experts in the field of minimally invasive spine surgery and produced a text that should be a standard for that subspecialty.

The book addresses minimally invasive surgery for the entire spine, starting in the cervical area and proceeding to the thoracolumbar spine. The text includes an excellent introductory chapter and describes the multiple fusion techniques performed via minimally invasive procedures. Classically, the two chapters on "facet rhizotomy" and "facet and epidural steroid injection" would not be included under minimally invasive spine surgery. Nevertheless, they are reasonable editions to the book.

Although many of the procedures described in this book can be performed through traditional open techniques, the authors nicely describe their minimally invasive counterpoints and often highlight the advantages of the minimal approach compared to the traditional open approach. Surgeons should first become experts in open approaches to the spine. Once they have mastered this fundamental armamentarium and know the anatomy well, they can apply the minimally invasive approaches to the spine that are so well described in this text. This book, which is very well done and timely, will become a standard text for any surgeon who performs minimally invasive spine surgery as well as for any surgeon who is developing his or her skills in this growing subspecialty.

Tuscon; Phoenix, Arizona

Volker K. H. Sonntag, MD

Preface

The use of minimally invasive spine surgical principles and techniques is rapidly escalating. It is finding its way, to one degree or another, into the practice of many spine surgeons. The enthusiasm for its use, on the part of both the spine surgeon and the patient, is impressive and dominates medical websites and Internet discussion as well as many surgical society meetings.

The reasons for this popularity are myriad. They include safety, blood loss, pain, and popularity among patients. With this enthusiasm, however, some self-reflection and careful consideration are necessary. As physicians, we must always consider the best available evidence that supports the use of any new technology. In this text, our aim is to consider the available evidence to support minimally invasive spine surgery. However, we must also consider safety, learning curve issues, and the high cost of these technologies. The latter two concerns may be more relevant for some conditions than for others. In varying degrees, there are also important considerations to be made for surgeon-specific issues.

We have attempted to assemble, in the pages that follow, a collection of works that provide the foundation for a minimalist approach to surgery of the spine. This should provide insight into pathology-specific and technique-related concerns. With this comes an understanding of the limitations of minimally invasive surgery, as well as its advantages, on a case-by-case basis. One must remember that "through small openings can lurk large complications." With this in mind, please read, enjoy, and learn from this collection of treatises from experienced authors/practitioners on the subject. We hope that you, as do we, find them to provide an objective, honest, and balanced approach to minimally invasive surgery and also to offer a useful reference for years to come.

Los Angeles, California — Burak M. Ozgur
Cleveland, Ohio — Edward C. Benzel
La Jolla, California — Steven R. Garfin

Contents

Contributors

Edward S. Ahn, PhD Chief Technology Officer, Angstrom Medica, Inc., Woburn, MA, USA

Christopher P. Ames, MD Associate Professor, Department of Neurosurgery, University of California-San Francisco, San Francisco, CA, USA

Henry E. Aryan, MD Clinical Instructor of Neurosurgery, Complex Spinal Reconstruction & Neurospinal Oncology, Department of Neurological Surgery, University of California-San Francisco, CA; Sierra Pacific Orthopaedic & Spine Center, Fresno, CA, USA

Farbod Asgarzadie, MD Assistant Professor, Department of Neurosurgery, Loma Linda University Medical Center, Loma Linda, CA, USA

Lissa C. Baird, MD Neurosurgery Resident, Division of Neurosurgery, University of California-San Diego, UCSD Medical Center, San Diego, CA, USA

Scott C. Berta, MD Neurosurgery Resident, Division of Neurosurgery, University of California-San Diego, UCSD Medical Center, San Diego, CA, USA

Sigurd H. Berven, MD Associate Professor in Residence, Department of Orthopaedic Surgery, University of California-San Francisco, UCSF Medical Center, San Francisco, CA, USA

Christopher M. Bono, MD Assistant Professor, Director of Spine Surgery, Department of Orthopaedic Surgery, Boston Medical Center, Boston University School of Medicine, Boston, MA, USA

Michael A. Chang, MD, PhD Department of Orthopedic Surgery, Wichita Clinic, Wichita, KS, USA

Andrew Cragg, MD Clinical Professor of Radiology, University of Minnesota, Edina, MN, USA

Oksana Didyuk, BS Research Assistant, Department of Neurosurgery, Providence Medical Center, Michigan Head and Spine Institute, Southfield, MI, USA

Kurt M. Eichholz, MD Assistant Professor of Neurological Surgery, Department of Neurological Surgery, Vanderbilt University Medical Center, Nashville, TN, USA

Richard G. Fessler, MD, PhD Professor, Department of Neurosurgery, Northwestern University; University of Chicago, Chicago, IL, USA

Steven R. Garfin, MD Professor and Chair, Department of Orthopaedic Surgery, University of California-San Diego, UCSD Medical Center, San Diego, CA, USA

Samuel A. Hughes, MD, PhD Neurosurgery Resident, Department of Neurological Surgery, Oregon Health & Science University, Portland, OR, USA

David H. Jho, MD, PhD Neurosurgery Resident, Department of Neurosurgery, Massachusetts General Hospital, Harvard Medical School, Boston, MA, USA

Hae-Dong Jho, MD, PhD Professor & Chairman, Department of Neuroendoscopy, Allegheny General Hospital, Drexel University College of Medicine, Pittsburgh, PA, USA

Iain H. Kalfas, MD, FACS Chairman, Department of Neurosurgery, Cleveland Clinic, Cleveland, OH, USA

Larry T. Khoo, MD Chief of Neurosurgery, UCLA Santa Monica Hospital, Assistant Professor of Neurological & Orthopedic Surgery, University of California-Los Angeles Comprehensive Spine Center, Los Angeles, CA, USA

Choll W. Kim, MD, PhD Assistant Professor, Department of Orthopaedic Surgery, University of California-San Diego, San Diego, CA, USA

Isador H. Lieberman, MD, MBA, FRCSC Professor of Surgery, Chairman, Medical Interventional and Surgical Spine Center, Cleveland Clinic Florida, Ft. Lauderdale, FL, USA

Adam K. MacMillan, BS Project Manager, Angstrom Medica, Inc., Woburn, MA, USA

Tobias Moeller-Bertram, MD Assistant Clinical Professor of Anesthesiology, Department of Anesthesiology, Center for Pain Medicine, University of California-San Diego, VA San Diego Healthcare Systems, San Diego, CA, USA

Peter O. Newton, MD Director of Scoliosis Service and Orthopaedic Research, Department of Orthopaedics, University of California-San Diego, Rady Children's Hospital, San Diego, CA, USA

Andrew D. Nguyen, MD, PhD Neurosurgery Resident Physician, Division of Neurosurgery and Senior Clinical Fellow, Division of Neuro-Interventional Radiology, University of California-San Diego Medical Center, San Diego, CA, USA

Donna D. Ohnmeiss, PhD President, Texas Back Institute Research Foundation, Plano, TX, USA

John E. O'Toole, MD Assistant Professor, Department of Neurosurgery, Rush Medical College of Rush University Medical Center, Chicago, IL, USA

Burak M. Ozgur, MD Director of Minimally Invasive Spine Surgery, Assistant Professor of Neurosurgery, Department of Neurosurgery, Cedars-Sinai Medical Center, Los Angeles, CA, USA

Pablo Pazmino, MD Department of Orthopaedic Surgery, Olympia Medical Center, Beverly Hills, CA, USA

Ramiro A. Perez de la Torre, MD Spine Fellow, Department of Neurosurgery, Providence Hospital, Southfield, MI, USA

Mick J. Perez-Cruet, MD, MS Director, Minimally Invasive Spine Surgery and Spine Program, Department of Neurosurgery, Providence Medical Center, Southfield, MI 48075; Adjunct Associate Professor, Oakland University, Rochester, MI, USA

Andrew Perry, MD Resident, Department of Orthopaedic Surgery, University of California-San Diego, San Diego, CA, USA

Ralph F. Rashbaum, MD Co-founder, Texas Back Institute Research Foundation, Plano, TX, USA

John J. Regan, MD Medical Director, Beverly Hills Spine Group, Cedar-Sinai Institute for Spinal Disorders, Beverly Hills, CA, USA

Hormoz Sheikh, MD Spine Research Fellow, Department of Neurosurgery, Providence Medical Center, Michigan Head and Spine Institute, Southfield, MI, USA

Jeff S. Silber, MD, DC Associate Professor, Department of Orthopaedic Surgery, Long Island Jewish Medical Center, New Hyde Park, NY; Albert Einstein School of Medicine, Bronx, NY, USA

Vartan S. Tashjian, MD, MS Department of Neurosurgery, University of California-Los Angeles, Santa Monica Orthopedic and Neurosurgical Spine Center, Los Angeles, CA, USA

Vickram Tejwani China Medical University, Shenyang, Liaoning, China; West Bloomfield, MI, USA

Alexander R. Vaccaro, MD, PhD Professor, Departments of Neurosurgery and Orthopaedic Surgery, Thomas Jefferson University and Rothman Institute, Philadelphia, PA, USA

Rohit B. Verma, MD Orthopaedic Spine Surgeon, Department of Orthopaedic Surgery, The Spine Institute; Department of Neurosurgery, The Chiari Institute, North Shore Manhasset Hospital, Great Neck, NY, USA

Mark S. Wallace, MD Professor of Clinical Anesthesiology, Program Director, Department of Anesthesiology, Center for Pain Medicine, University of California-San Diego Medical Center, La Jolla, CA, USA

Anthony T. Yeung, MD DISC – Desert Institute for Spine Care, Phoenix, AZ; Volunteer Clinical Associate Professor, Department of Orthopaedic Surgery, University of California-San Diego School of Medicine, San Diego, CA, USA

Christopher A. Yeung, MD DISC – Desert Institute for Spine Care, Phoenix AZ; Department of Orthopaedic Surgery, Volunteer Clinical Faculty, University of California-San Diego School of Medicine, San Diego, CA, USA

Hansen A. Yuan, MD Professor, Department of Orthopaedic and Neurological Surgery, State University of New York-Syracuse Medical Center, Syracuse, NY, USA

Barón Zárate Kalfópulos, MD Orthopaedic Surgeon, Department of Spinal Surgery, National Rehabilitation Center, Universidad Nacional Autónoma de Mexico, México Distrito Federal, Mexico

General Introduction and Principles of Minimally Invasive Spine Surgery

1

Burak M. Ozgur

"Minimally invasive" seems to be the catchphrase that we hear a lot these days. No matter which type of surgery we are talking about, it is what every patient wants to be told that he or she is a candidate for. Furthermore, nearly all surgeons want to claim that what they do is minimally invasive. For we must consider the alternative: No surgeon will announce that what he or she does is "maximally invasive."

What does it mean to do something minimally invasive? Is it all about the incision? Does it all come down to the cosmetic end result? How about the postoperative pain scale, narcotic use, and hospital stay? Certainly, we must consider the extent of soft tissue injury and blood loss. These are all considerations for the surgical decision making and techniques chosen.

The first consideration should always begin with the proper diagnosis and the appropriate treatment options. We should never put our patients in a compromised position due to inexperience and/or inadequate exposure. The end result, whether it is a decompression or an instrumentation, should be effectively and functionally the same whether done minimally- invasively or in a traditional open manner.

I think of minimally invasive surgery as a state of mind. It is a conscious decision and conscientious effort made by the surgeon to try and preserve as much native tissue, usually muscles and ligaments, as possible without compromising the surgical goal. In fact, I look at it as the surgeon sneaking in, performing the surgery, and sneaking out with minimal disruption. We must remember that the body is continuously trying to self-medicate, self-brace, and autofuse. This is clearly evident in scoliosis, in various forms of arthritis, and even demonstrated to the extreme with autoimmune disorders.

Burak M. Ozgur (✉)
Director of Minimally Invasive Spine Surgery, Assistant Professor of Neurosurgery, Department of Neurosurgery, Cedars-Sinai Medical Center, Los Angeles, CA 90048, USA
e-mail: bozgur@gmail.com

We've only relatively recently begun to appreciate how our extent of bony and soft tissue decompression and manipulation may have more consequences beyond the case at hand. We know that if we take too much of the mesial facets and disrupt the joint capsules, for example, this may have long-term effects for our patients. I would even go as far as saying that a significant proportion of the degenerative cascade of spinal revision surgery is iatrogenic in nature secondary to extensive soft tissue dissection, devitalizing this underappreciated soft tissue component of the surgical exposure. Consider how aggressively we bovie soft tissue away as we dissect broadly with our Cobb curettes until we are able to place our oversized, crank-style, self-retaining retractors. Numerous studies have already demonstrated the extensive muscle necrosis caused by these types of exposures and retractors. Certainly, these types of exposures are necessary with some types of cases. However, often times we may be able to achieve our goals with less dissection and destruction.

Figure 1.1 demonstrates the dramatic difference in a traditional exposure and soft tissue disruption in comparison to Fig. 1.2, which demonstrates a less invasive approach. Figure 1.3 demonstrates the use of successive dilating tubes in achieving access. Figure 1.4 demonstrates

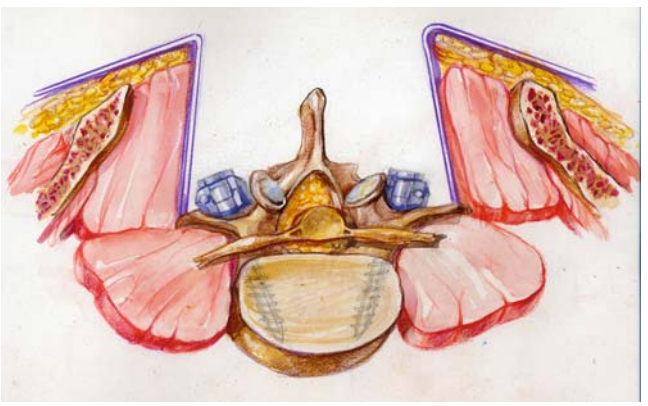

Fig. 1.1 An artist's rendition of a traditional surgical exposure

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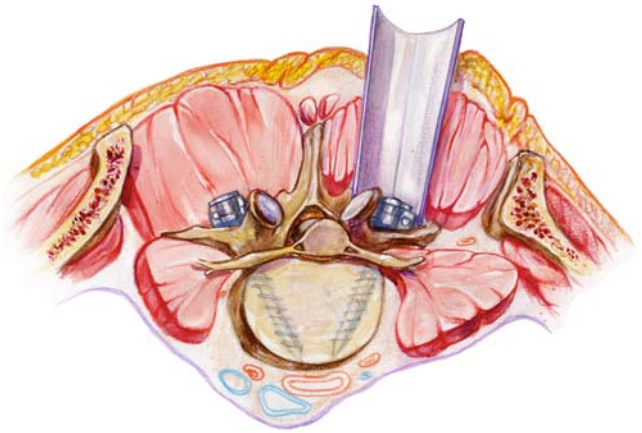

Fig. 1.2 An artist's rendition of a minimally invasive surgical exposure through a tubular-type retractor

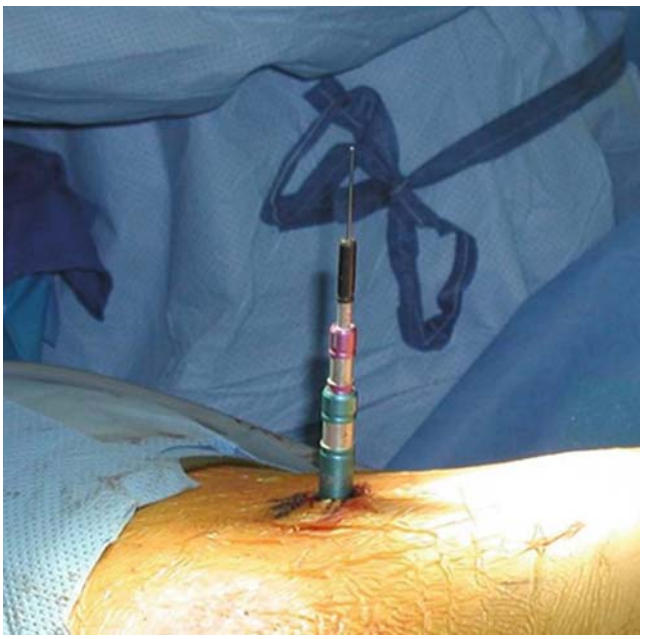

Fig. 1.3 Photo demonstrating the placement of successive dilating tubes

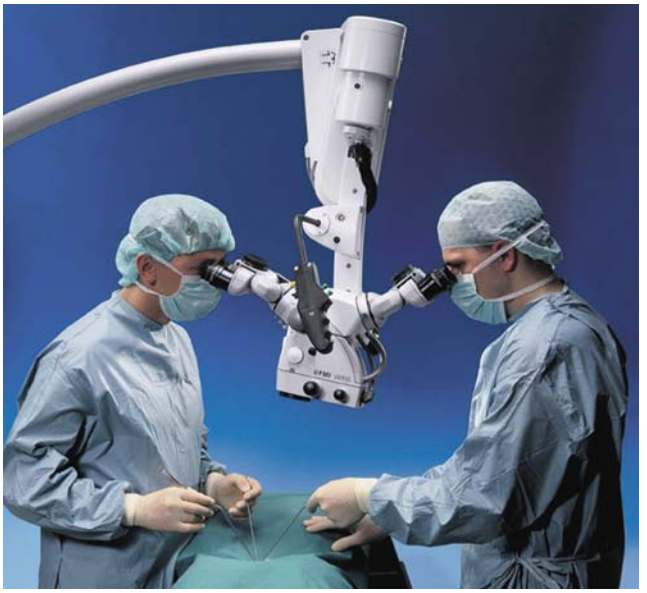

Fig. 1.4 Use of the intraoperative microscope helpful not only for lighting and magnification, but also for teaching and for others to view the operative field. (From Mayer HM, ed. *Minimally Invasive Spine Surgery: A Surgical Manual*. 2nd ed. Berlin: Springer; 2006., p. 13. Reprinted with kind permission of Springer Science + Business Media)

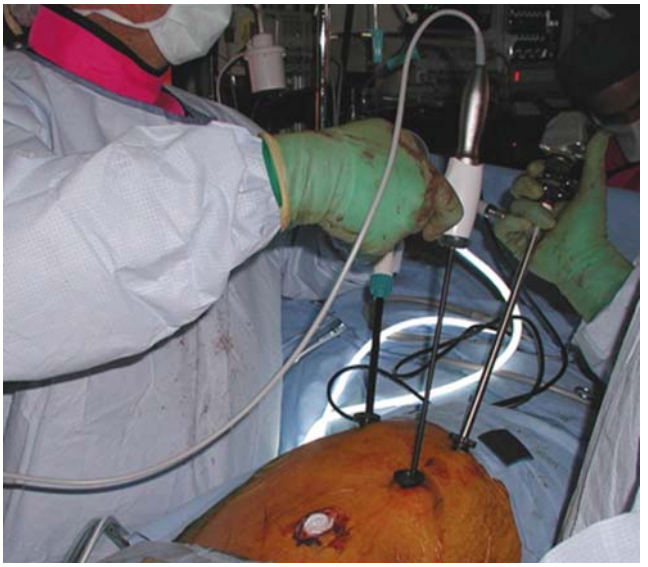

Fig. 1.5 Photo demonstrating the use of laparoscopic instruments

the common use of an operative microscope to both enhance visualization for the surgeon as well as allow an assistant to participate in the operating room. Otherwise, minimally invasive procedures make it very difficult for anyone else (particularly residents and fellows) to learn or assist in the case. Figure 1.5 shows a case being done with the assistance of an endoscope. Finally, Figs. 1.6 and 1.7 show, in dramatic fashion, the potential size difference in surgical incisions between traditional surgery and minimally invasive surgery.

In explaining to patients the pathophysiology of spinal disorders, I like to bring in an analogy to a tire. I describe the intervertebral disc as a tire in that, when healthy, the disc is like a new tire full of air. However, as we age, we lose air in our tire and the vertebral bodies get closer together. This concept is visually demonstrated in Fig. 1.8. Now consider this analogy over many levels and through progressive deterioration as in adult degenerative scoliosis. Expanding the tire analogy, one can

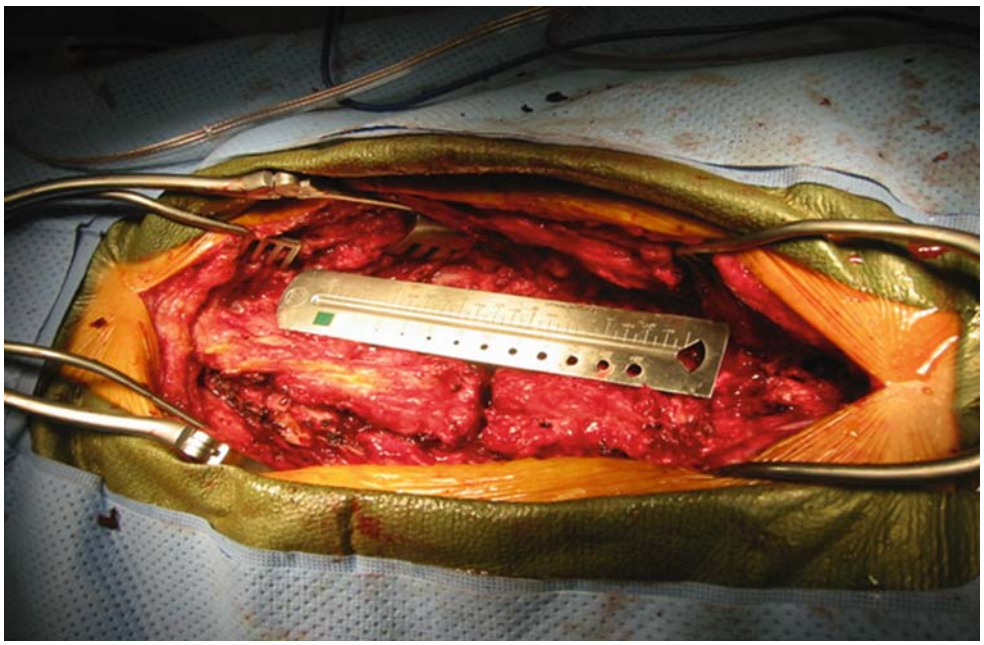

Fig. 1.6 Photo demonstrating a traditional surgical opening

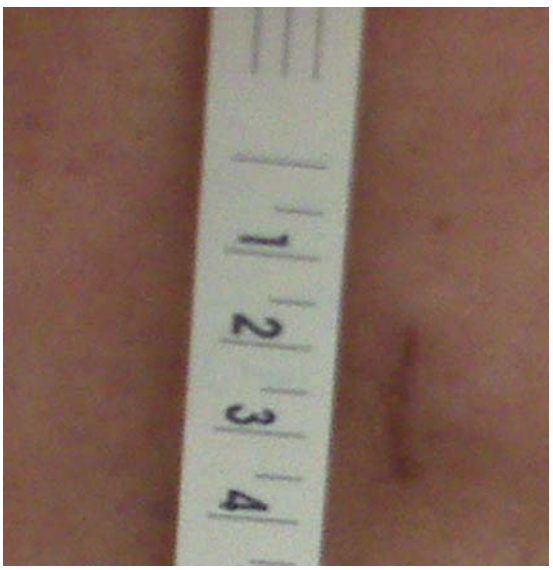

Fig. 1.7 Postoperative photo of a well-healed minimally invasive surgical incision

consider the entire car. The healthy spine and car are demonstrated in Fig. 1.9. In the deteriorating spine, not only does the intervertebral height diminish, but also the facet joints become exposed to additional stressors and we see evidence for instability by way of spondylolisthesis in various dimensions. Hence, depending where in the degenerative cascade the patient presents to medical attention, we may see differing complexities in deformity. Once again considering the car analogy, we can see how this process is cumulative over multiple levels and may culminate in a rather complex deformity. This concept is demonstrated in Fig. 1.10.

Anecdotal experience shows that patients not only experience less blood loss and suffer less pain, but require less hospital stay as well. What demonstrates the most dramatic effect on the economy, however, is how much sooner the patient is able to return to work. Unfortunately, literature does not yet exist to show these trends, but these are definite patterns demonstrated by experienced surgeons. Not all cases may be performed in a minimally invasive manner. Ultimately, surgeons must do a better job of making the correct diagnosis and then presenting the options to their patients. I am confident that in time the literature will support the efficacy and demonstrate the benefits of these techniques while providing patients with far better options for treating spinal disorders.

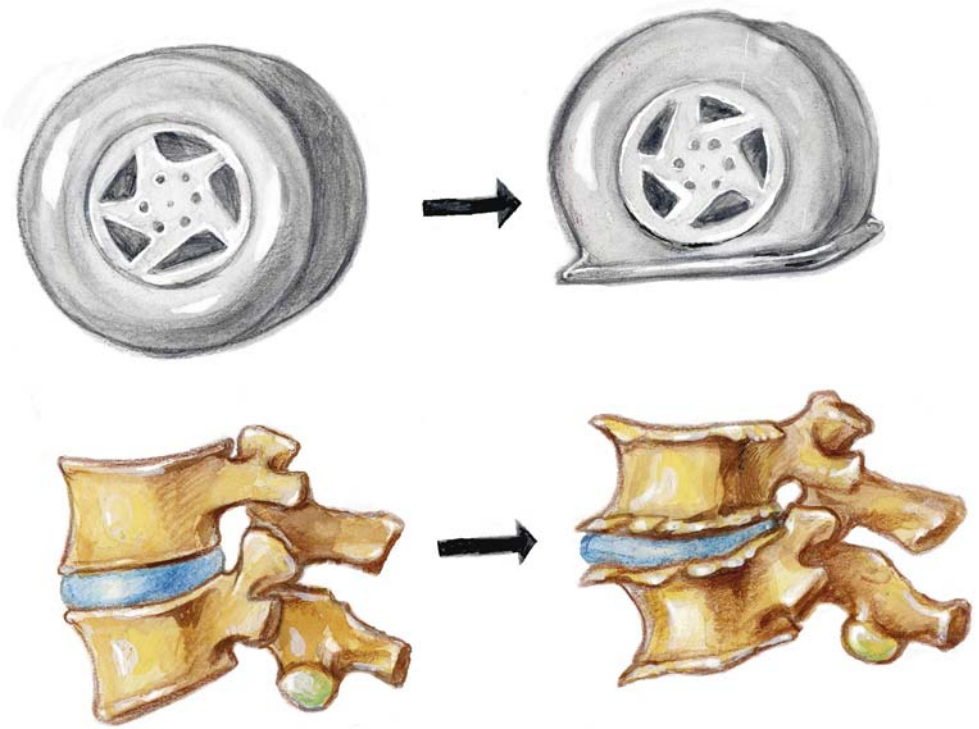

Fig. 1.8 Cartoon depicting analogy between a flat tire and a degenerating spinal disc

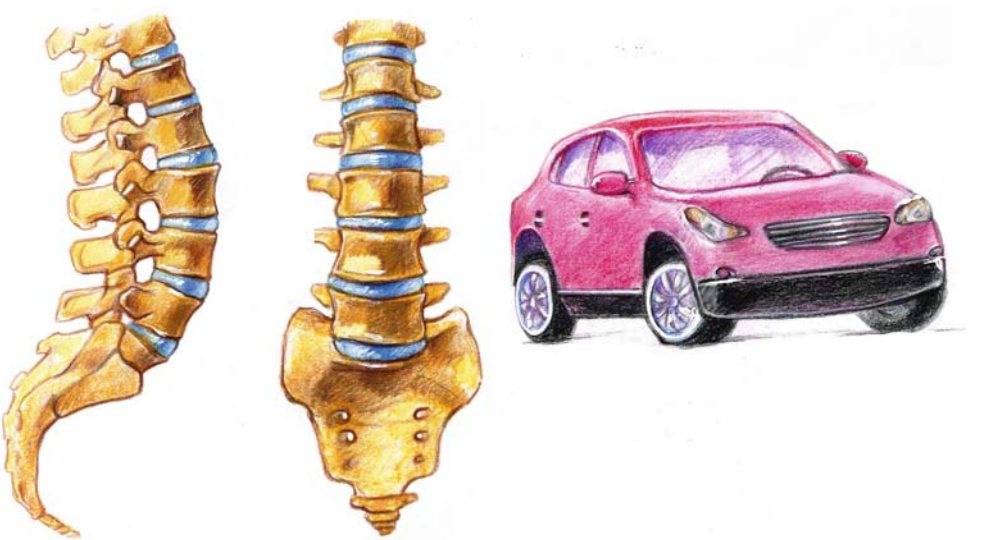

Fig. 1.9 Cartoon depicting analogy between a healthy spine and a new car

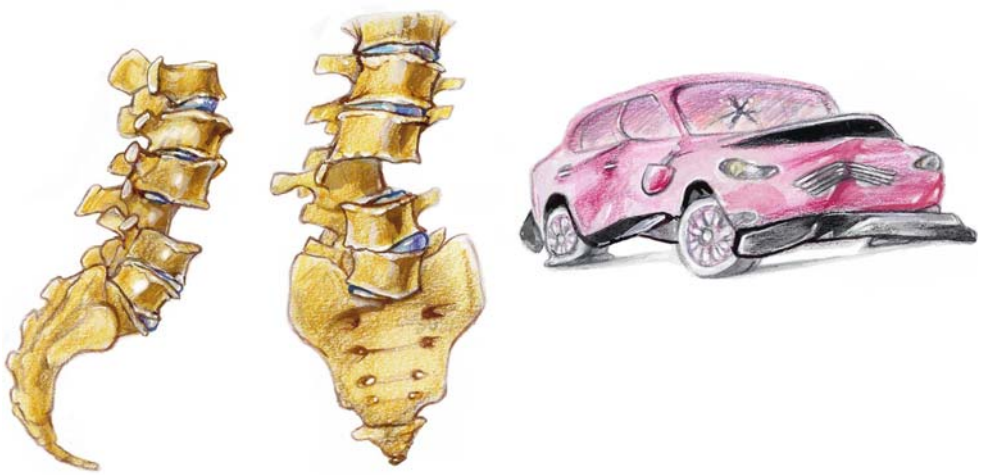

Fig. 1.10 Cartoon depicting analogy between adult degenerative scoliosis, with multilevel bony degeneration, twisting, and degenerative disc disease, to an aged car with flat tires, unbalanced alignment, and *wear and tear*

Image-Guided Spinal Navigation: Principles and Clinical Applications

2

Iain H. Kalfas

Introduction

Image-guided spinal navigation is a computer-based surgical technology that was developed to improve the intraoperative orientation to the unexposed anatomy during complex spinal procedures [1, 2]. It evolved from the principles of stereotaxy, which neurosurgeons have used for several decades to help localize intracranial lesions. Stereotaxy is defined as the localization of a specific point in space using three-dimensional coordinates. The application of stereotaxy to intracranial surgery initially involved the use of an external frame attached to the patient's head. However, the evolution of computer-based technologies has eliminated the need for this frame and has allowed for the expansion of stereotactic technology into other surgical fields, in particular, spinal surgery.

The management of complex spinal disorders has been greatly influenced by the increased acceptance and use of spinal instrumentation devices as well as the development of more complex operative exposures. Many of these techniques place a greater demand on the spinal surgeon by requiring a precise orientation to that part of the spinal anatomy that is not exposed in the surgical field. In particular, the various fixation techniques that require placing bone screws into the pedicles of the thoracic, lumbar, and sacral spine, into the lateral masses of the cervical spine, and across joint spaces in the upper cervical spine require "visualization" of the unexposed spinal anatomy. Although conventional intraoperative imaging techniques such as fluoroscopy have proven useful, they are limited in that they provide only two-dimensional imaging of a complex three-dimensional structure. Consequently, the surgeon is required to extrapolate the third dimension based on an interpretation of the images and knowledge of the pertinent anatomy. This so-called dead reckoning of the anatomy can result in varying degrees of inaccuracy when placing screws into the unexposed spinal column.

Several studies have shown the unreliability of routine radiography in assessing pedicle screw placement in the lumbosacral spine. The rate of penetration of the pedicle cortex by an inserted screw ranges from 21–31% in these studies [3–5]. The disadvantage of these conventional radiographic techniques in orienting the spinal surgeon to the unexposed spinal anatomy is that they display, at most, only two planar images. While the lateral view can be relatively easy to assess, the anteroposterior (AP) or oblique view can be difficult to interpret. For most screw fixation procedures, it is the position of the screw in the axial plane that is most important. This plane best demonstrates the position of the screw relative to the neural canal. Conventional intraoperative imaging cannot provide this view. To assess the potential advantage of axial imaging for screw placement, Steinmann et al. used an image-based technique for pedicle screw placement that combined computed tomography (CT) axial images of cadaver spine specimens with fluoroscopy. This study demonstrated an improvement in pedicle screw insertion accuracy with an error rate of only 5.5% [6].

Image-guided spinal navigation minimizes much of the "guesswork" associated with complex spinal surgery. It allows for the intraoperative manipulation of multiplanar computed tomographic (CT) images that can be oriented to any selected point in the surgical field. Although it is not an intraoperative imaging device, it provides the spinal surgeon with superior image data compared to conventional intraoperative imaging technology (i.e., fluoroscopy). It improves the speed, accuracy, and precision of complex spinal surgery while, in most cases, eliminating the need for cumbersome intraoperative fluoroscopy.

I.H. Kalfas (✉)
Department of Neurosurgery, Cleveland Clinic, Cleveland, OH 44195, USA
e-mail: kalfas@neus.ccf.org

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Principles of Image-Guided Spinal Navigation

The use of an image-guided navigational system for localizing intracranial lesions has been previously described [7, 8]. Image-guided navigation establishes a spatial relationship between preoperative CT image data and its corresponding intraoperative anatomy. Both the CT image data and the anatomy can be viewed as a three-dimensional coordinate system, with each point in that system having a set of specific *x, y,* and *z* Cartesian coordinates. Using defined mathematical algorithms, a specific point in the image data set can be "matched" to its corresponding point in the surgical field. This process is called "registration" and represents the critical step of image-guided navigation. A minimum of three points needs to be matched, or registered, to allow for accurate navigation.

A variety of navigational systems have evolved over the past decade. The common components of most of these systems include an image processing computer workstation interfaced with a two-camera optical localizer (Fig. 2.1). When positioned during surgery, the optical localizer emits infrared light toward the operative field. A handheld navigational probe mounted with a fixed array of passive reflective spheres serves as the link between the surgeon and the computer workstation (Fig. 2.2). Alternatively, passive reflectors may be attached to standard surgical instruments. The computer workstation knows the spacing and positioning of the passive reflectors on each navigational probe or customized trackable surgical instrument. The infrared light that is transmitted toward the operative field is reflected back to the optical localizer by the passive reflectors. This information is then relayed to the computer workstation, which can use it to calculate the precise location of the instrument tip in the surgical field as well as the location of the anatomic point on which the instrument tip is resting.

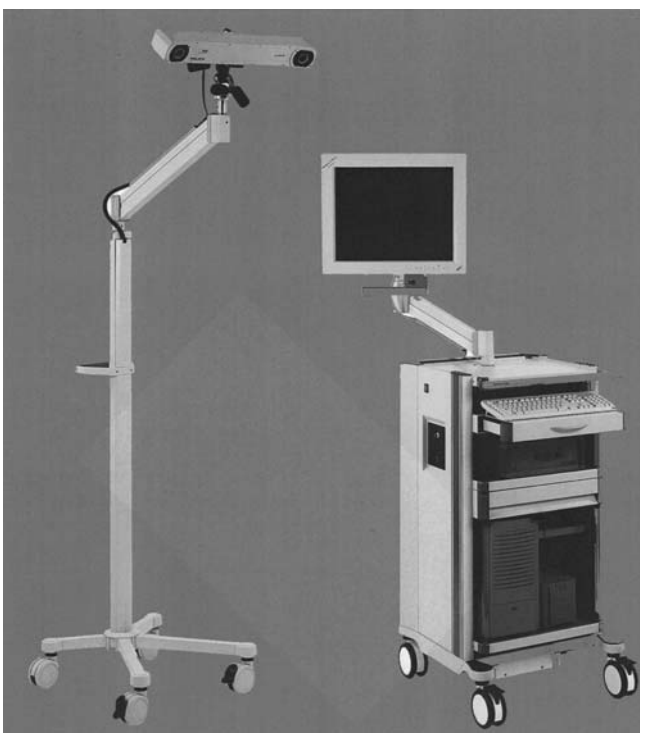

Fig. 2.1 Image-guided navigational workstation with infrared camera localizer system

Fig. 2.2 Navigation probe and drill guide for spinal surgery

The initial application of navigational principles to spinal surgery was not intuitive. Early navigational technology applied to intracranial surgery used an external frame mounted to the patient's head to provide a point of reference to link preoperative image data to intracranial anatomy. This was not practical for spinal surgery. The current generation of intracranial navigational technology uses reference markers or fiducials that are attached to the patient's scalp prior to imaging. However, the use of these surface-mounted fiducials for spinal navigation is not practical because of accuracy issues related to a greater degree of skin movement over the spinal column [9, 10]. This is less of a problem with intracranial applications because of the relatively fixed position of the overlying scalp to the attached fiducials.

The application of navigational technology to spinal surgery involves using the rigid spinal anatomy itself as a frame of reference. Bony landmarks on the exposed surface of the spinal column provide the points of reference necessary for image-guided navigation. Specifically, any anatomic landmark that can be identified intraoperatively as well as in the preoperative image data set can be used as a reference point. The tip of a spinous or

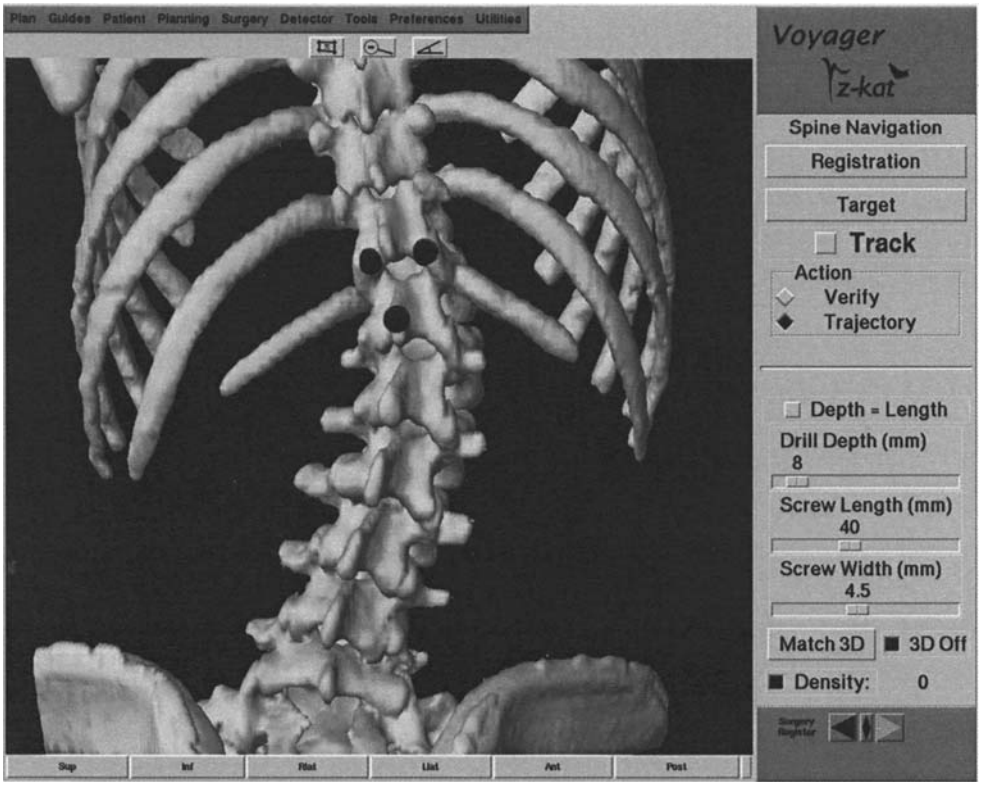

Fig. 2.3 Navigational workstation screen demonstrating a paired-point registration plan for the insertion of T12 pedicle screws. Three discrete bony landmarks are selected at the T12 level. In this case, the lateral margins of the two T12 transverse processes and the tip of the T12 spinous process have been selected

transverse process, a facet joint, or a prominent osteophyte can all serve as potential reference points (Fig. 2.3). Since each vertebra is a fixed, rigid body, the spatial relationship of the selected registration points to the vertebral anatomy at a single spinal level is not affected by changes in body position.

Two different registration techniques can be used for spinal navigation: paired-point registration and surface matching. Paired-point registration involves selecting a series of corresponding points in a computed tomography (CT) or magnetic resonance imaging (MRI) data set and in the exposed spinal anatomy. The registration process is performed immediately after surgical exposure and prior to any planned decompressive procedure. This allows for the use of the spinous processes as registration points.

A specific registration point in the CT image data set is selected by highlighting it with the computer cursor. The tip of the probe is then placed on the corresponding point in the surgical field, and the reflective spheres on the probe handle are aimed toward the camera. Infrared light from the camera is reflected back, allowing the spatial position of the probe's tip to be identified. This initial step of the registration process effectively "links" the point selected in the image data with the point selected in the surgical field. When a minimum of three such points is registered, the probe can be placed on any other point in the surgical field and the corresponding point in the image data set will be identified on the computer workstation.

Alternatively, a second registration technique called "surface matching" can be used. This technique involves selecting multiple nondiscrete points only on the exposed surface of the spine in the surgical field. This technique does not require the prior selection of points in the image set, although several discrete points in both the image data set and the surgical field are frequently required to improve the accuracy of surface mapping. The positional information of these points is transferred to the workstation, and a topographic map of the selected anatomy is created and "matched" to the patient's image set [11].

Typically, paired-point registration can be done more quickly than surface mapping. The average time needed for paired-point registration is 10–15 seconds. The time needed for surface mapping is much longer, with difficult cases requiring as much as 10–15 minutes. With the need to perform several registration processes during each surgery, this time difference can significantly impact the length of the navigational procedure and the surgery itself [12].

The purpose of the registration process is to establish a precise spatial relationship between the image space of

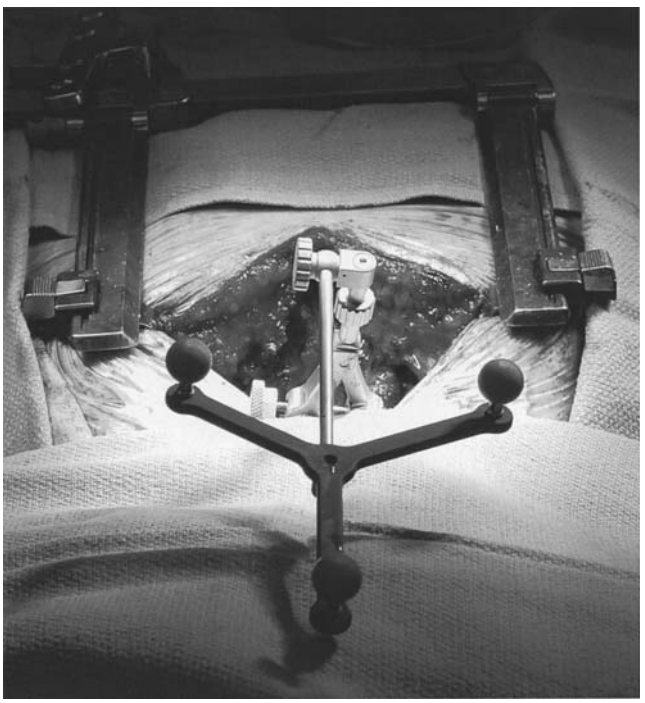

Fig. 2.4 Reference frame attached to a spinous process in the surgical field. The reference frame monitors inadvertent movement of the spinal anatomy that may affect navigational accuracy

the data and the physical space of the patient's corresponding surgical anatomy. If the patient is moved after registration, this spatial relationship is distorted, making the navigational information inaccurate. This problem can be minimized by the optional use of a spinal tracking device, which consists of a separate set of passive reflectors mounted on an instrument that can be attached to the exposed spinal anatomy (Fig. 2.4). The position of the reference frame can be tracked by the camera system. Movement of the frame alerts the navigational system to any inadvertent movement of the spine. The system can then make correctional steps to keep the registration process accurate and eliminate the need to repeat the registration process. The disadvantages of using a tracking device are the added time needed for its attachment to the spine, the need to maintain a line of sight between it and the camera, and the inconvenience of having to perform the procedure with the device placed in the surgical field. It is particularly cumbersome when image-guided navigation is used during cervical procedures.

Alternatively, image-guided spinal navigation can be performed without a tracking device [1, 12]. This involves acknowledging the effect of patient movement on the accuracy of image-guided navigation and maintaining reasonably stable patient positioning during the relatively short amount of time needed (i.e., 10–20 s) for the selection of each appropriate screw trajectory. Patient movement can potentially occur with respiration, from the surgical team leaning on the table, or from a change of table position. Movement associated with patient respiration is negligible and does not require any tracking, even in the thoracic spine. Although movement associated with leaning on the table or repositioning the table or the patient will affect registration accuracy, it can be easily avoided during the short navigational procedure. If inadvertent patient movement does occur, the registration process can be repeated. Repeating the registration process is easiest when using the shorter paired-point technique as opposed to the more time-consuming surface mapping technique.

When the registration process has been completed, the probe can be positioned on any surface point in the surgical field, and three separate reformatted CT images centered on the corresponding point in the image data set are immediately presented on the workstation monitor. Each reformatted image is referenced to the long axis of the probe. If the probe is placed on the spinal anatomy directly perpendicular to its long axis, the three images will be in the sagittal, coronal, and axial planes. A trajectory line representing the orientation of the long axis of the probe will overlay the sagittal and axial planes. A cursor representing a cross section through the selected trajectory will overlay the coronal plane. The insertional "depth" of the trajectory can be adjusted to correspond to selected screw lengths. As the depth is adjusted, the specific coronal plane will also adjust accordingly, with the position of the cursor demonstrating the final position of the tip of a screw placed at that depth along the selected trajectory. As the probe is moved to another point in the surgical field, the reformatted images as well as the position of the cursor and trajectory line will also change. The planar orientation of the three reformatted images will also change as the probe's angle relative to the spinal axis changes. When the probe's orientation is not perpendicular to the long axis of the spine, the images are displayed in an oblique, or orthogonal, plane. Regardless of the probe's orientation, the navigational workstation will provide the surgeon with a greater degree of anatomic information than can be provided by any intraoperative imaging technique.

The application of image-guided navigation to spinal surgery is directed by the complexity of the procedure and, specifically, by the need to "visualize" the unexposed spinal anatomy. Image-guided navigation can be used with or without standard intraoperative imaging techniques (i.e., fluoroscopy). In either case, image-guided navigation provides the surgeon with an improved orientation to the pertinent spinal anatomy, which subsequently facilitates the accuracy and effectiveness of the procedure.

Clinical Applications

Image-guided spinal navigation was initially evaluated for the insertion of pedicle screws in the thoracic and lumbosacral spines of cadaver specimens. The accuracy of screw insertion was documented by plain film radiography and thin-section CT imaging of the instrumented levels. All inserted pedicle screws were satisfactorily placed [2]. The clinical application of image-guided spinal navigation began with its use in lumbosacral pedicle fixation [1, 13, 14]. Other spinal applications gradually evolved, including transoral decompression, cervical screw fixation, thoracic pedicle fixation, anterior thoracolumbar decompression and fixation procedures, and application to spinal metastasis [12, 15–20].

Pedicle Fixation

Pedicle fixation has gained acceptance as an effective and reliable method of spinal stabilization. However, because of the variations of pedicle anatomy within each patient, the safe and precise placement of pedicle screws can be difficult. Suboptimal screw placement can result in varying degrees of neural injury and fixation failure. These complications can be minimized if the surgeon is provided with accurate spatial orientation to each pedicle to be instrumented prior to screw insertion.

Image-guided spinal navigation can now be used routinely in place of fluoroscopy for the insertion of pedicle screws in both the thoracic and lumbosacral spine. Although fluoroscopy provides real-time imaging of spinal anatomy, the views generated represent only two-dimensional images of a complex three-dimensional structure. Manipulation of the fluoroscopic unit can reduce this problem, but these maneuvers can be cumbersome and time-consuming. Other disadvantages include the radiation exposure and the need to wear lead aprons during the procedure. Fluoroscopy cannot provide a view of the spinal anatomy in the axial plane. It is this axial view provided by image-guided navigation that makes it superior to fluoroscopy for spinal screw fixation procedures.

The application of image-guided navigation to the spine involves obtaining a preoperative CT scan through the appropriate spinal segments to be instrumented. The images consist of a three-dimensional volume data set of contiguous axial computed tomography images. Alternatively, MRI data may also be used. The image data is then transferred to the computer workstation via optical disc or a high-speed data link. If paired-point registration is to be used, three to five reference points for each spinal segment to be instrumented are selected and stored in the image data set.

Intraoperatively, a standard exposure of the spinal levels to be instrumented is performed. A lateral radiograph can be obtained to confirm the appropriate level. The computer workstation and camera localizer are then positioned. The infrared camera detector is mounted at the foot of the table and aimed rostrally for thoracic and lumbosacral procedures.

Image-guided navigation is typically used prior to any planned decompression in order to utilize the intact posterior elements as registration points. The first spinal segment to be instrumented is registered using either the paired-point or surface mapping technique. When the registration process has been completed, the navigational workstation will calculate and display a registration error (expressed in millimeters) that is directly dependent on the surgeon's registration technique. The error presented does not represent a linear error but rather a volumetric calculation comparing the spacing of registration points in the surgical field to the spacing of the corresponding points in the image data set. This figure is, at best, a relative indicator of accuracy.

A better method of ensuring registration accuracy is the verification step. This step is typically performed immediately after completing either registration process. The surgeon places the navigational probe on a discrete landmark in the surgical field. With the navigational system now tracking the movement and position of the probe, the trajectory line and cursor on the workstation screen will, if accurate registration has been achieved, move to the corresponding point in the image data set. If registration accuracy has not been achieved, the cursor and trajectory line may rest on a point other than that selected in the surgical field. If this occurs to a significant degree, the registration process needs to be repeated. This step is more of an absolute indicator of registration accuracy and is important to perform prior to proceeding with navigation.

When an accurate registration of the first spinal level to be instrumented has been verified, standard bony landmarks for pedicle localization are used to approximate the screw entry point. A drill guide is placed on this entry point, and the navigation probe is passed through the guide. The navigational system is activated, permitting tracking of the probe in the surgical field. Three separate reformatted views are displayed on the workstation screen. Each view represents a separate plane passing through the selected point in the surgical field. For most pedicle fixation cases, these views typically consist of a sagittal, an axial, and a coronal reconstruction. A trajectory line referenced to the long axis of the probe is superimposed on the sagittal and axial views. A round cursor, representing a

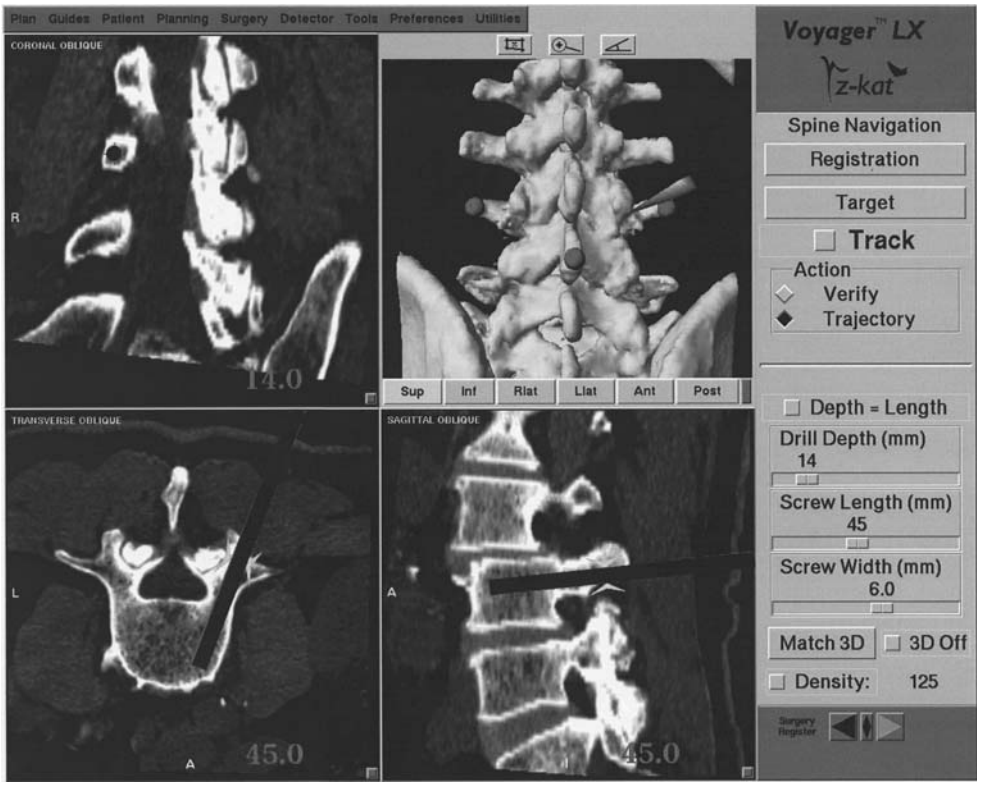

Fig. 2.5 Workstation screen demonstrating navigation for an L3 pedicle screw

cross section through the selected trajectory, is superimposed on the coronal view. As the probe is moved through the surgical field, the position of the trajectory line and cursor will change accordingly. Both the width of the trajectory line and the diameter of the cursor can be adjusted to match the relative diameter of the pedicle screws to be used. The length of the trajectory line can also be adjusted (Fig. 2.5).

As the probe is placed on each pedicle entry point, the images on the workstation screen are presented in real time. As the angle of the probe is adjusted in the axial and sagittal planes, the images immediately update to show the corresponding trajectories. The depth of the coronal view can be adjusted to show the cross-sectional anatomy at any point along the selected trajectory. The orientation of each pedicle to be instrumented can be assessed rapidly and accurately. Any errors in trajectory or entry point selection can be determined and corrected by adjusting the position of the probe and the drill guide through which it passes.

When a satisfactory screw entry point and trajectory have been selected, the probe is removed from the drill guide, a drill (3-mm diameter) is inserted through the guide, and a pilot hole along the selected trajectory is created. The purpose of using a drill guide is to preserve the physical trajectory and entry point information acquired through the navigation process. Without a drill guide, it may be difficult to precisely position a drill or pedicle probe on the same point and with the same trajectory selected during navigation. When the pilot hole is placed, a sound can be passed down the hole to ensure adequate positioning. Navigation is then performed for the contralateral pedicle and a pilot hole is drilled. The process of navigating each spinal level, including registration, accuracy verification, navigation, and pilot hole placement, typically takes no more than 2–3 minutes.

For each additional vertebrae to be instrumented, a new set of registration points at that level is selected. This method, termed "segmental registration," eliminates any potential discrepancy in anatomic orientation that may be related to a change in patient position between the preoperative CT scan and surgery. Since each vertebra is a fixed, rigid body, the spatial relationship of the selected registration points to the vertebral anatomy at a single spinal level is not affected by changes in body position.

After all pilot holes have been drilled, they are tapped and the appropriate size screws inserted. C-arm fluoroscopy or serial radiographs are not required. Typically, the combined time for both navigation and screw insertion for a two-level lumbar fixation procedure is approximately 8–10 minutes when using a paired-point registration technique. This figure can be considerably higher when using a

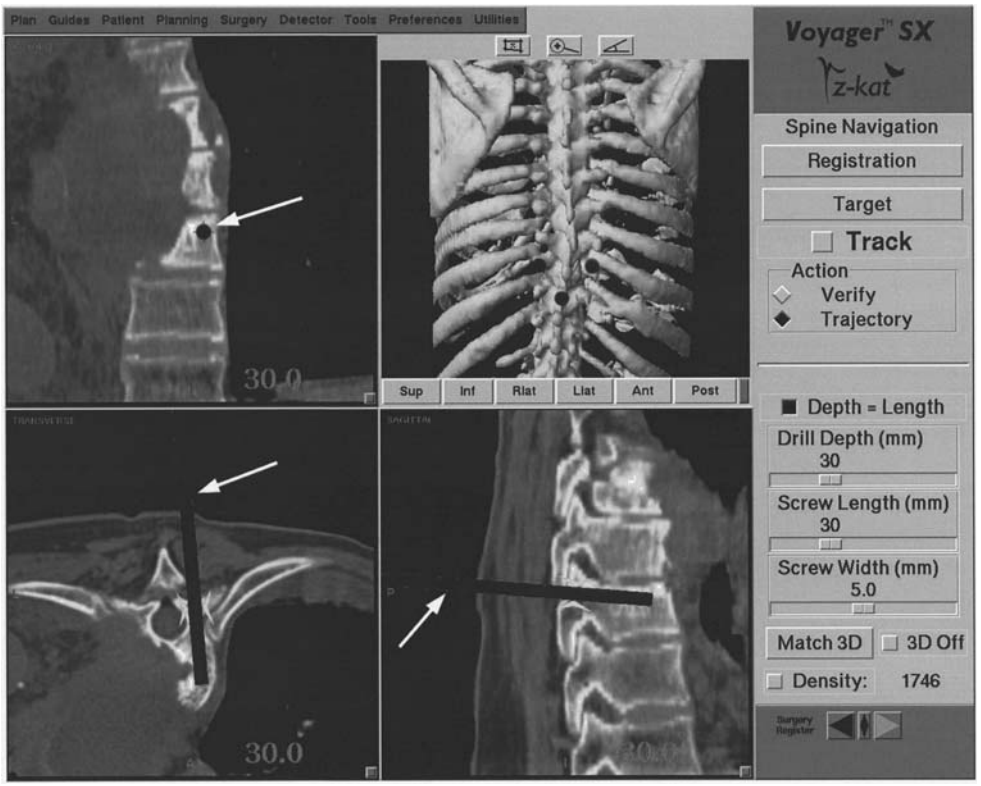

Fig. 2.6 Workstation screen demonstrating navigation for a T8 pedicle screw in a patient with mycotic aneurysm of the aorta

surface mapping technique due to the greater time it takes to achieve adequate registration with surface mapping.

In addition to screw placement in the large pedicles of the lumbosacral spine, image-guided navigation can also facilitate screw placement into the smaller pedicles of the thoracic spine (Fig. 2.6). The added precision for screw placement into thoracic pedicles greatly expands the fixation options for managing the unstable thoracic spine and cervicothoracic junction.

Image-guided navigation can also be used in place of fluoroscopy for the placement of interbody cages in the lumbosacral spine. During removal of the intervertebral disc, the navigational probe can be inserted into the evacuated disc space. With the trajectory length set at zero, the three reformatted images displayed provide optimal spatial orientation to the disc space, allowing for precise placement of the cages [Figs. 2.7(a), (b)].

Minimally Invasive Spinal Surgery

The advantage of minimally invasive spinal surgical procedures is that soft tissue disruption is minimized through the use of smaller skin incisions, with the potential for less postoperative pain and earlier recovery from the surgery. The disadvantage of this approach is that the surgeon has a limited exposure to the surgical anatomy and therefore a lower degree of orientation to the nonvisualized anatomy. This increases the difficulty in selecting accurate screw trajectories through the spinal anatomy and typically necessitates the use of longer periods of C-arm fluoroscopy than would normally be used with a more open approach. This limitation can be managed with image-guided spinal navigation, minimizing or eliminating the need for fluoroscopy.

For minimally invasive pedicle fixation procedures, two paraspinal incisions are made over the spinal levels to be instrumented. Dissection of the transverse process, facet complex, and pedicle entry site is performed, and minimally invasive tubular or oval retractors are inserted on each side. Once exposed, the navigational process proceeds as it would with a conventional approach. For each level to be instrumented, three registration points are selected. These typically include the tips of the two transverse processes, the facet joints, or the tip of the spinous process, which can be accessed through a small, midline stab incision. The navigational probe is then placed through each retractor to navigate the pedicle trajectory on each side. Fluoroscopic imaging is unnecessary.

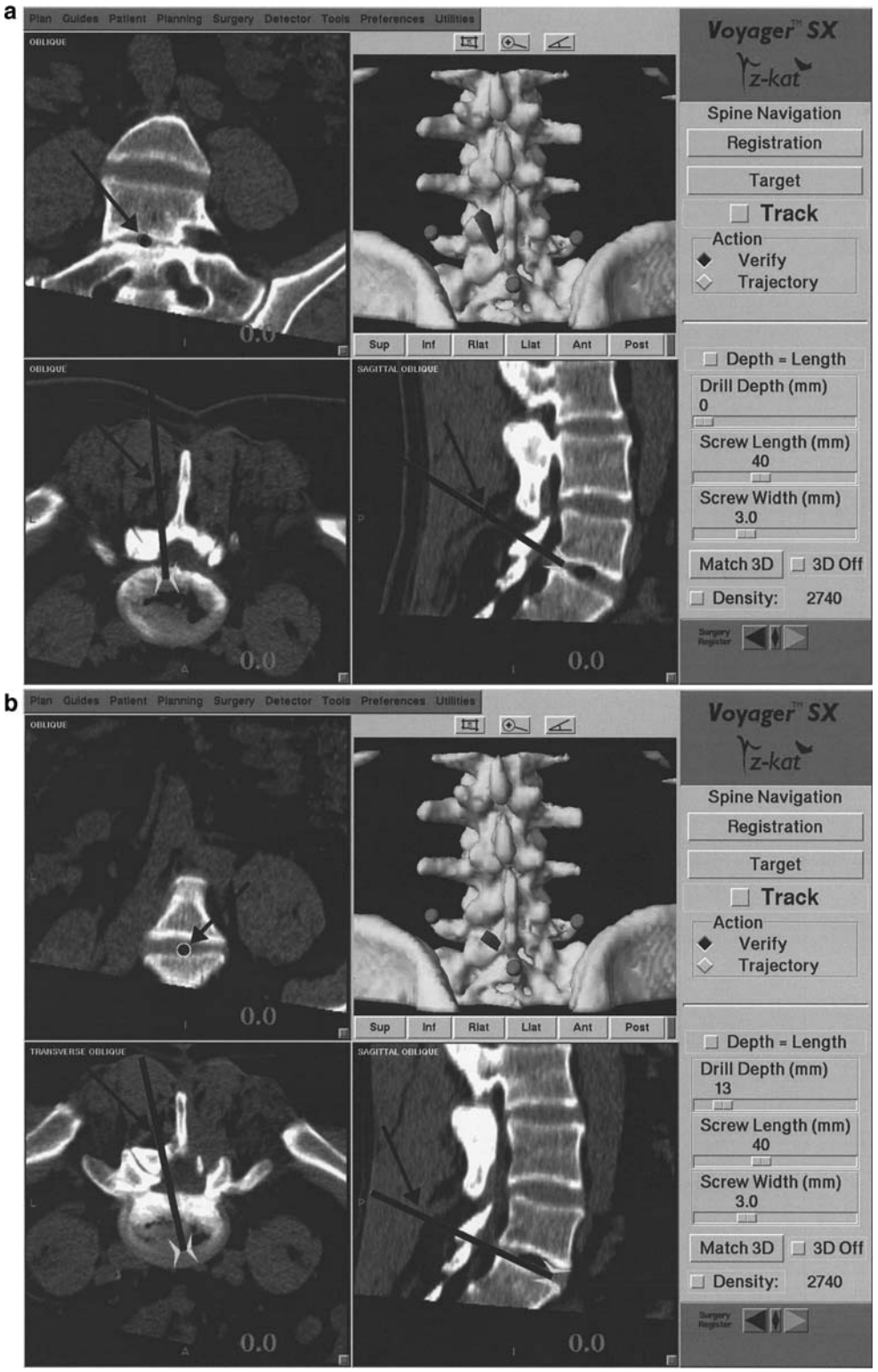

Fig. 2.7 (**a**) Workstation screen prior to L5-S1 disc excision for a posterior interbody fusion (probe tip location and trajectory highlighted by *arrows*). (**b**) Workstation screen after L5-S1 disc excision. The depth within the disc space and the extent of disc removal can be determined prior to cage or bone graft insertion (robe tip location and trajectory highlighted by *arrows*)

C1-2 Transarticular Screw Fixation

This procedure involves the passage of a screw through the pars interarticularis of C2, across the facet joint, and into the lateral mass of C1. The risks of screw insertion include injury to the vertebral artery if the screw is placed too laterally or ventrally, injury to the spinal cord if the screw is placed too medially, and failure to engage the lateral

mass of C1 if the screw trajectory is too ventral. The insertion of a screw on either side may be contraindicated if the pars interarticularis of C2 is too narrow. The procedure is typically performed bilaterally using fluoroscopic guidance.

The selection of the appropriate screw entry site and trajectory requires a thorough understanding of the atlantoaxial anatomy. Although fluoroscopy provides real-time imaging of the relevant spinal anatomy, the views generated represent only two-dimensional images of a complex three-dimensional anatomic region. Manipulation of the fluoroscopic unit can reduce this problem, but these maneuvers can be cumbersome and time-consuming. Other disadvantages include the radiation exposure and the need to wear lead aprons during the procedure. Fluoroscopy cannot provide a view of the spinal anatomy in the axial plane. It is this axial view provided by image-guided navigation that makes it superior to fluoroscopy for spinal screw fixation procedures. The application of image-guided navigation to this procedure adds a significant layer of accuracy for proper screw placement.

The technique for applying image-guided navigation to posterior C1–C2 screw fixation involves acquiring a preoperative CT scan that extends from the lower occipital region to C3. The image data is transferred to the computer workstation and can be used to create a preoperative screw trajectory plan. A proposed entry point and target can be selected at the C2 and C1 levels, respectively. The image data set can then be manipulated in multiple planes between these two points to demonstrate the position of a screw placed along the selected trajectory. In addition to a sagittal image that demonstrates the same information provided by lateral fluoroscopy, two other images are presented. One of the images lies perpendicular to the sagittal image along the selected trajectory. It represents an orthogonal view that lies approximately midway between the coronal and axial planes through the spine. It demonstrates a second view of the selected trajectory.

An additional view demonstrates an image oriented perpendicular to the long axis of the probe and, therefore, the selected trajectory. A cursor superimposed on this image can show the position of the screw tip along the selected trajectory at millimetric increments. By scrolling through this image, the proposed position of the screw along the selected trajectory can be assessed along its entire path. While this planning technique does not ensure safe screw placement intraoperatively, it can preoperatively alert the surgeon to avoid screw placement in patients with insufficient anatomy and to select an alternate approach.

Intraoperatively, the patient is positioned and the posterior C1-2 complex is exposed. A wire (cable) and bone graft stabilization procedure at the C1-2 level is performed prior to navigation and screw insertion. Performing this step first minimizes any independent motion between C1 and C2 during navigation and makes the tap and screw insertion easier. If a reference frame is used, it is typically attached to the spinous process of C2.

Following placement of the graft and cable, —three to five registration points are selected at the C2 level. It is not necessary to include registration points at C1. Although the spatial relationship of C1 and C2 may change between the preoperative scanned position and the intraoperative position, the ability of image-guided navigation to facilitate accurate screw placement is not significantly affected. The technical difficulty of this procedure is the accurate passage of the screw through the narrow pars interarticularis of C2. The lateral mass of C1 is a relatively large target that can be easily reached provided there are a reasonably acceptable realignment of C1 and C2 as well as an optimal positioning of the screw within the appropriate C2 anatomy. While the relative position of C1 and C2 in both the preoperative image set and in the surgical field is important, it is not critical enough to interfere with the process of image-guided navigation.

Two separate stab incisions are made on either side of the midline at the C7–T1 level. A drill guide is placed through one of the stab incisions and passed through the paravertebral musculature and into the operative field. A small divot is drilled at the proposed entry site in order to provide for secure placement of the drill guide. The registration process is performed at the C2 level and its accuracy confirmed using the verification step. The probe is passed through the drill guide, and as its position is adjusted in the surgical field, the images on the workstation screen will adjust accordingly to show the corresponding trajectory in two separate planes and the projected location of the screw tip in the third plane. Orientation to the correct screw position can be assessed rapidly and accurately (Fig. 2.8). Any errors in trajectory or entry point selection can be determined and corrected by adjusting the position of the probe and the drill guide through which it passes. When the correct screw insertion parameters have been selected, the probe is removed from the drill guide and a drill inserted. A hole is drilled along the selected trajectory, tapped, and the appropriate length screw inserted. The process is repeated on the opposite side.

The purpose of the drill guide is to preserve the physical trajectory and entry point information just acquired through the navigation of that pedicle. If a drill guide is not used, it may be difficult to precisely position a drill or pedicle probe on the same point and with the same trajectory previously conveyed by the navigational probe after probe removal.

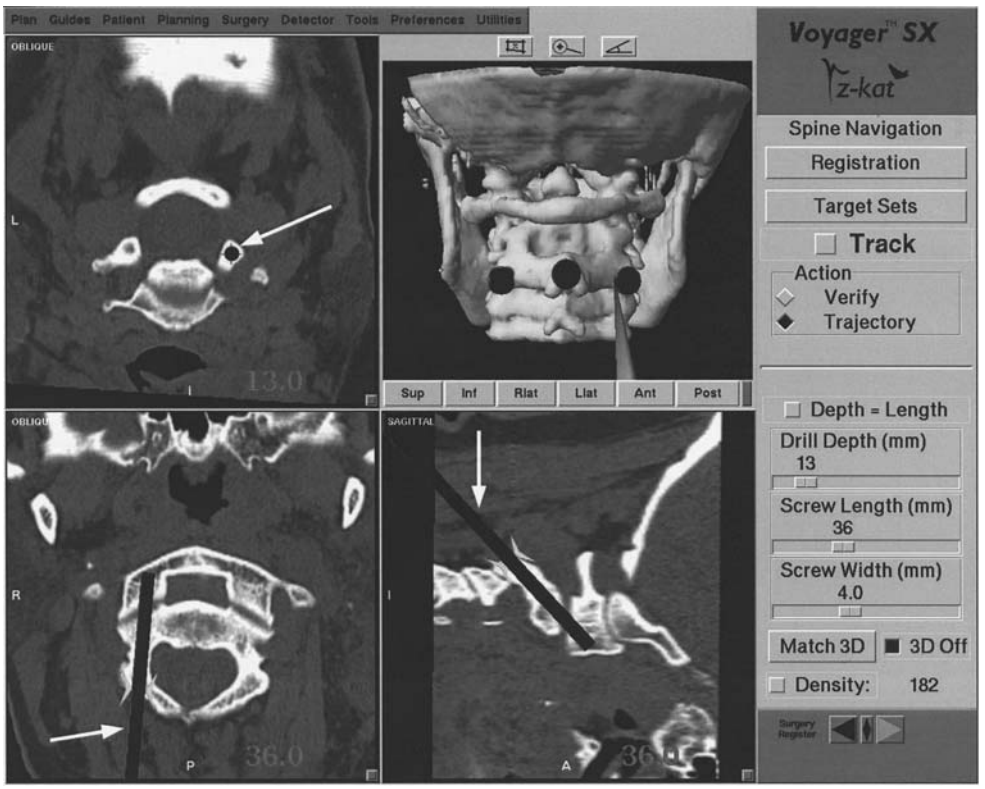

Fig. 2.8 Workstation screen demonstrating a trajectory for the insertion of a C1-2 transarticular screw. The *lower right* screen shows the trajectory in the sagittal plane. The *lower left* screen represents an orthogonal plane lying between the axial and coronal planes. It conveys the medial-lateral trajectory. The *upper left* screen represents a plane that is perpendicular to the other two images. It demonstrates the location of the screw tip inserted along the selected trajectory at the indicated depth (screw trajectory and tip location highlighted by *arrows*)

While image-guided navigation does not guarantee accurate screw placement, it does provide the surgeon with a greater degree of anatomical information than fluoroscopy alone. The addition of fluoroscopy to this navigational technique provides the greatest degree of precision to the procedure. In this case, however, navigational technology significantly reduces the time of intraoperative fluoroscopic usage, as it is typically used only to help position the patient preoperatively and as a final check of the selected trajectory in the sagittal plane immediately following the navigational step.

Segmental C1-2 Screw Fixation

As an alternative to transarticular screw fixation, segmental fixation of C1-2 can be used for managing atlantoaxial instability [21]. The procedure involves placing a screw into each of the two lateral masses of C1 and two screws down the pedicles of C2. The polyaxial screw heads on each side are then connected with rods. Although this approach potentially reduces the risk of injury to the vertebral artery during screw insertion, it does not eliminate the risk altogether. As with the transarticular technique, precise anatomic orientation is required to avoid arterial or neural injury. Image guidance can supplement intraoperative fluoroscopy in order to provide the necessary orientation for accurate screw insertion.

As with the transarticular screw fixation technique, a preoperative CT is obtained. The posterior C1-2 spine is exposed, and a wire and cable fixation procedure is carried out. Registration is first performed at C1 for placement of the C1 lateral mass screws. The three registration points typically used at C1 include the midline posterior tubercle and the bilateral points marked by the junction of the small pedicle of C1 with its lateral mass (immediately above the two exiting C2 nerve roots). Once registered, the correct trajectory into the lateral mass can be displayed on the workstation screen and the screws inserted [Figs. 2.9(a) and (b)]. To use image guidance for inserting C2 pedicle screws, the same registration points are used at C2 as those used for transarticular fixation (the C2 spinous process and the two lateral margins of the C2-3 facet). The entry point for the screw is more lateral and the trajectory more medially oriented than for a transarticular screw. The navigation probe is placed through a drill guide onto this entry point, and the selected trajectory is displayed on the workstation screen. When the correct entry point and trajectory have

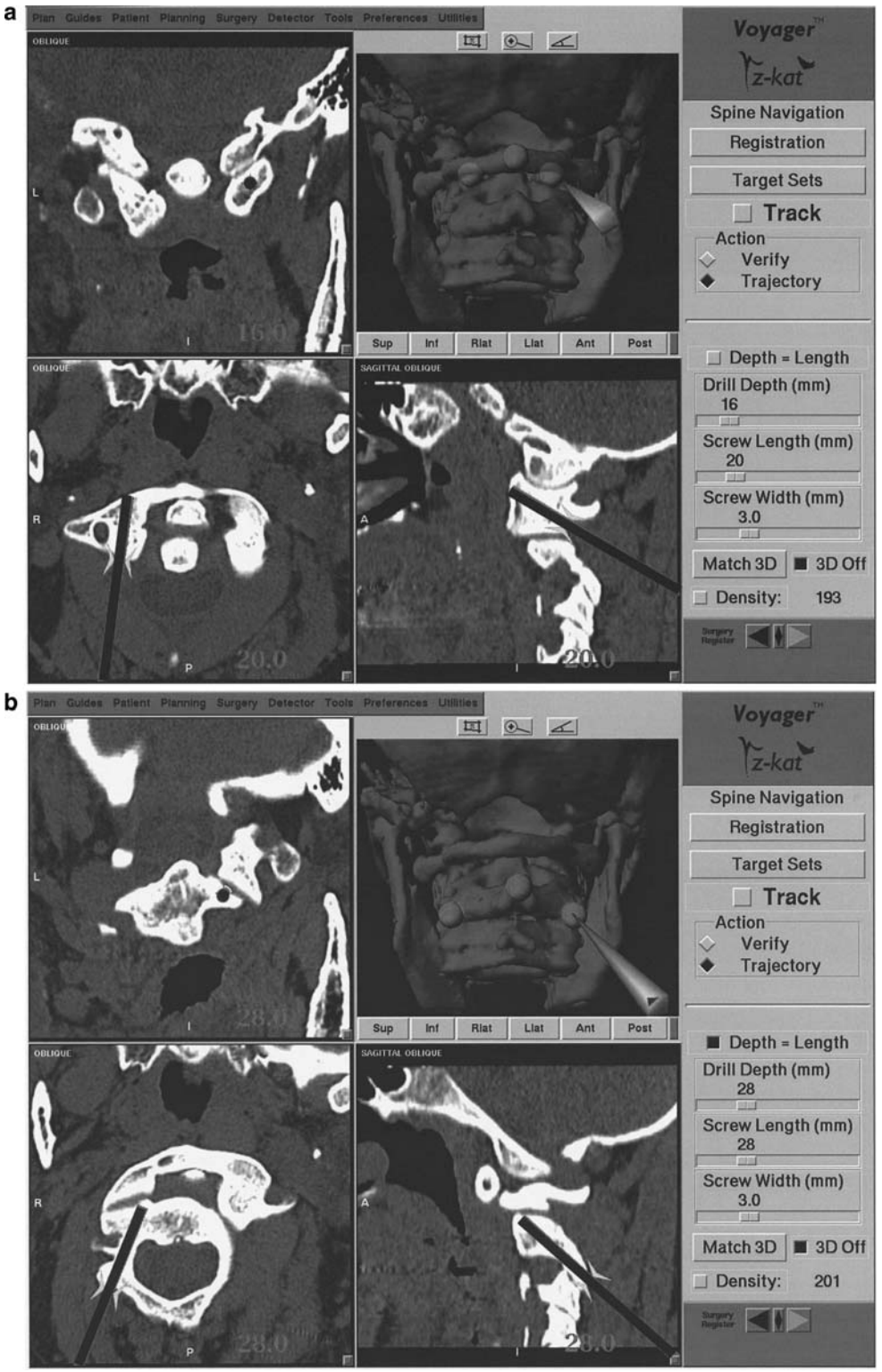

Fig. 2.9 (**a**) Workstation screen demonstrating navigational information for the placement of a screw into the lateral mass of C1. (**b**) Workstation screen demonstrating navigational information for the placement of a screw into the pedicle of C2

been selected, the probe is removed, a drill is inserted, and the pilot hole is drilled. The process is then repeated for the other side. The heads of the screws are then connected with two short rods.

Transoral Surgery

Transoral decompression of the upper cervical spine typically requires intraoperative fluoroscopy to help maintain

proper anatomic orientation during the procedure. Although orientation in the sagittal plane is easy to obtain with fluoroscopy, the depth and medial-lateral orientation are more difficult to assess. Image-guided technology can be used to orient the surgeon in multiple planes during transoral surgery [12, 22].

Unlike other spinal applications of image guidance, discrete registration points are not readily available during transoral surgery. In this setting, surface-mounted markers (fiducials) are applied to the patient prior to obtaining the preoperative CT. Typically, two fiducials are applied to the mastoid processes and two are applied to the lateral orbital margins or to both malar eminences. The nasal septum and the anterior tubercle of C1 can also be used as an inherent registration point.

The patient is positioned in a three-point head holder. The registration process is performed prior to draping the patient using the surface-mounted fiducials. Because the registration points will not be accessible during the procedure, a reference frame is used for transoral navigation. This allows for changes in patient positioning during surgery without the need to reregister. The reference frame can be attached to the three-point head holder.

During the procedure, the probe can be placed into the site of the decompression. Reformatted sagittal, axial, and coronal CT images are immediately generated, providing the surgeon with a precise orientation to the pertinent surgical anatomy. In particular, orientation in the axial plane minimizes the risk of lateral deviation toward the vertebral artery during the decompression (Fig. 2.10). If a posterior fixation is indicated following transoral decompression, the same CT image data set can be used for C1-2 screw placement.

Anterior Thoracolumbar Surgery

Image-guided spinal navigation can be applied to anterior thoracolumbar surgery to help orient the surgeon to the extent of anterior decompression and to facilitate the precise placement of fixation screws. Although the selection of reference points for anterior spinal surgery is limited by the relative lack of prominent bony landmarks on the anterior aspect of the spinal column, the degree of accuracy required is less than that needed for most posterior screw fixation procedures. This degree of accuracy, termed "clinically relevant accuracy," will change according to the procedure being performed. It represents the degree of accuracy needed to achieve a particular surgical task. For example, the insertion of a C1-2 transarticular

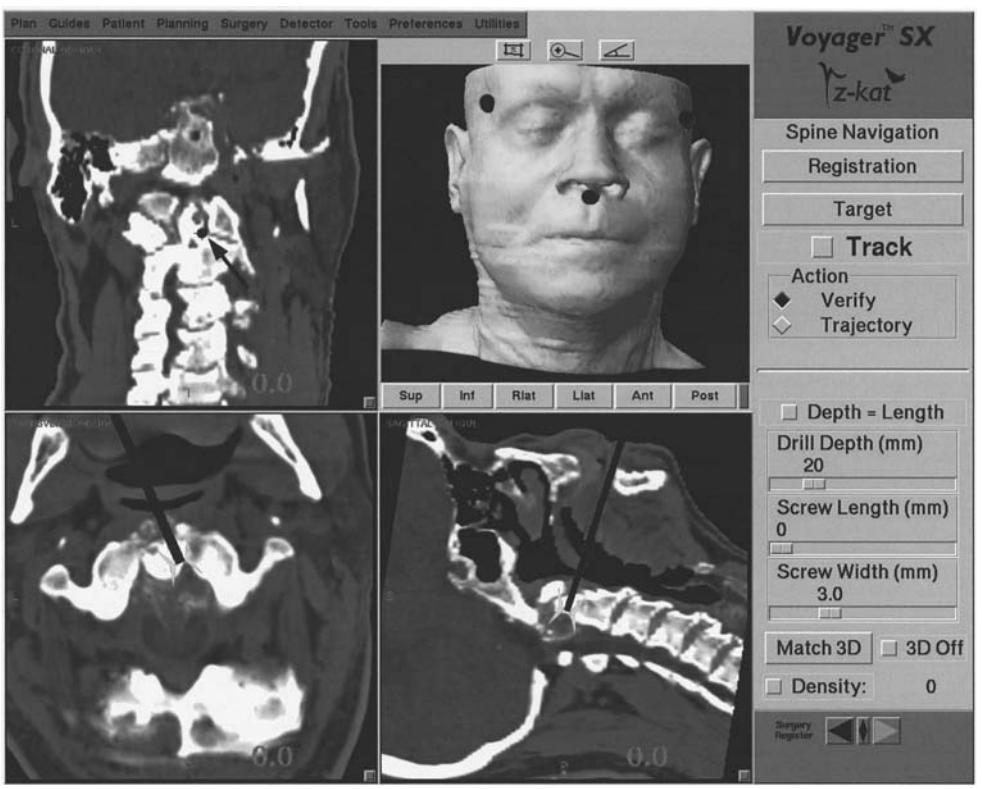

Fig. 2.10 Workstation screen demonstrating navigational information during transoral decompression (probe tip location and trajectory highlighted by *arrows*)

screw has a higher clinically relevant accuracy demand than placing an anterior fixation screw across a large thoracic or lumbar vertebral body. In both cases, image-guided navigation provides clinically relevant accuracy more consistently than fluoroscopy alone.

Potential registration points for the use of image-guided navigation in anterior thoracolumbar surgery include selected landmarks on the vertebral endplates, pedicles, head of the rib, and prominent ventral osteophytes. In general, higher registration errors can be tolerated because of the lower accuracy requirements for most anterior thoracolumbar procedures compared to posterior screw fixation procedures. The accuracy verification step performed immediately after registration can further confirm the achievement of clinically relevant accuracy before proceeding with navigation.

During anterior decompression, the probe can be placed into the partially decompressed site to orient the surgeon to the contralateral margin of the spinal column and, more importantly, to the location of the epidural space [Fig. 2.11(a)]. An orientation to tumor margins can also be obtained by placing the probe into the partially decompressed tumor bed. Following decompression, image guidance can be used to guide anterior fixation screws across the vertebrae at either end of the corpectomy site [Fig. 2.11(b)].

Other Spinal Applications

Image-guided technology has several other applications in the management of complex spinal disorders. Any procedure in which intraoperative imaging is required to improve a surgeon's orientation to nonexposed spinal anatomy can benefit from image guidance. Other procedures to which image guidance has been applied include anterior screw fixation for nondisplaced odontoid fractures, cervical corpectomy, and the removal of paraspinal neoplasms. The navigational workstation also serves as a platform for providing intraoperative image manipulation capabilities. This allows the surgeon to scroll through reformatted CT images in multiple planes, providing for optimal preoperative planning as well as improved intraoperative anatomic assessment.

Pitfalls of Image-Guided Spinal Navigation

While image-guided spinal navigation has proven to be a versatile and effective tool for facilitating complex surgical procedures, it can be prone to several potential problems prior to and during its use. In general, these pitfalls and errors are related to issues of the accuracy, technique, and overall ease of use of the technology during surgery. A thorough understanding of these potential problems is required to ensure the efficient and effective use of image-guided navigation for spinal surgery.

Like any other computer-based technology, image-guided navigation is highly dependent on the quality of the information imported into the system. While obtaining the properly formatted CT images and having them correctly transferred to the navigational workstation is important, the critical step of image guidance is the registration process. If the surgeon takes too casual an approach to registration, inaccurate information will be displayed during intraoperative navigation.

Another important principle of image guidance is the understanding that the navigational information provided needs to be correlated with the surgeon's own knowledge of the surgical anatomy and the appropriate screw trajectories through that anatomy. Image-guided navigation is not a replacement for the surgeon knowing the pertinent spinal anatomy and surgical technique. It merely serves to help confirm a surgeon's estimation of the nonexposed anatomy by providing image information that exceeds that provided by intraoperative fluoroscopy. Despite the advantages of image guidance, the surgeon must ultimately assess the information provided by these systems and determine if it correlates with his or her estimation of the nonexposed anatomy and the proposed surgical plan. If a good correlation exists, the surgical step can be carried out. However, if a sufficient correlation is not present, the surgeon needs to reassess both the spinal anatomy and the image-guided registration accuracy before proceeding.

Image-guided technology also has varying degrees of intraoperative functionality depending on the features of the navigational system used. This translates into an ease-of-use factor that can either simplify or complicate the overall procedure. Typically, the use of the surface mapping registration technique and a reference frame add time to the navigational procedure, frequently making it longer and more complicated than using fluoroscopy alone. The use of the paired-point registration technique without a reference frame simplifies the spinal navigation process. Using this approach, the insertion of four pedicle screws typically takes no more than 8–10 minutes. By optimizing the ease of use of navigational technology, standard fluoroscopy becomes unnecessary for most spinal screw fixation procedures.

Fluoroscopic Navigation

Fluoroscopic navigation is the combination of standard fluoroscopy with image-guided navigational technology. It was developed to address the difficulties of some earlier

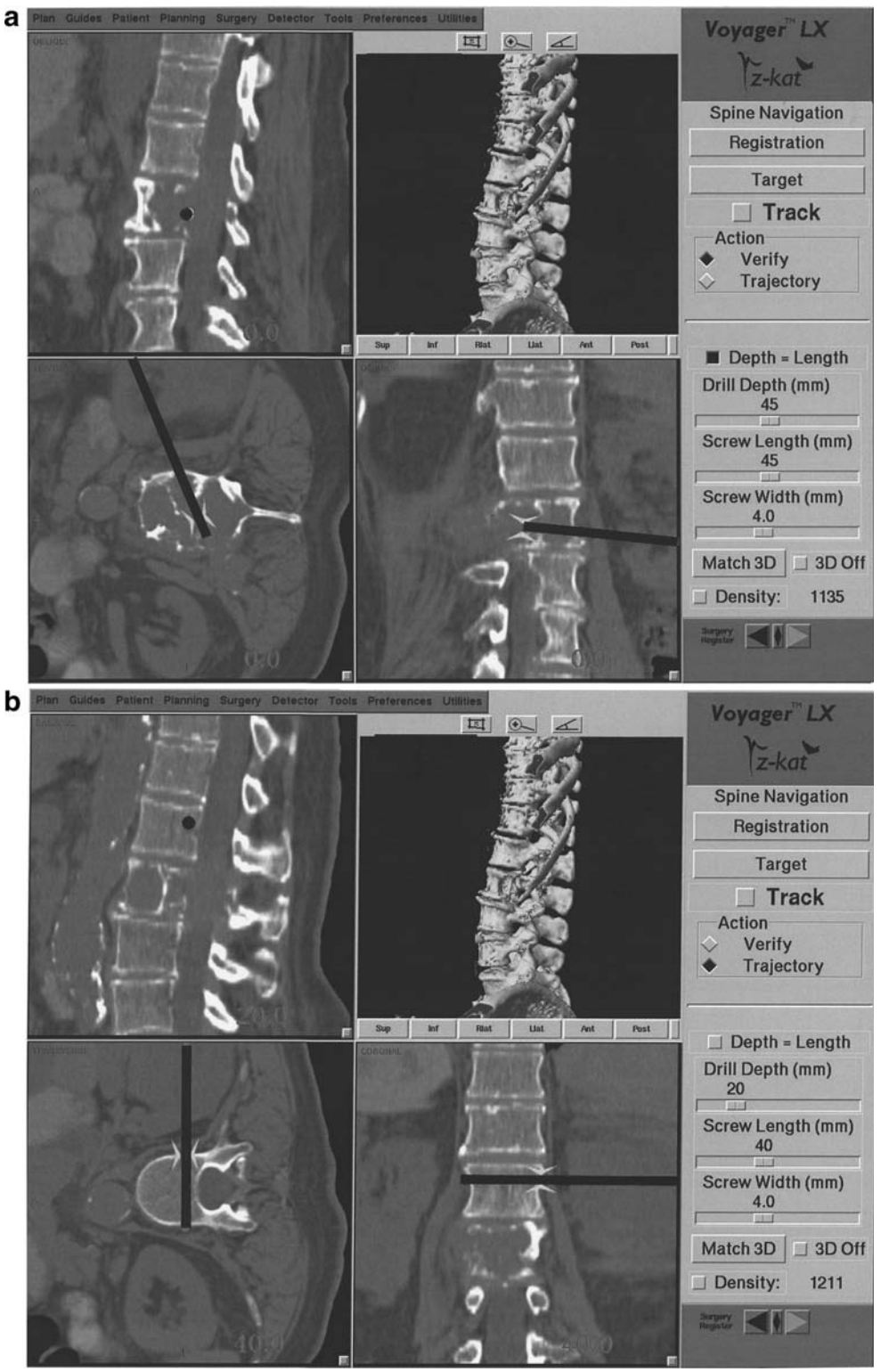

Fig. 2.11 (**a**) Workstation screen demonstrating navigation during removal of an L2 metastasis. Orientation to the contralateral side as well as the epidural space can be obtained. (**b**) Workstation screen demonstrating a selected trajectory for an anterior lumbar fixation screw

image-guided systems that typically took much longer to use than standard fluoroscopy [23]. Its advantage is that it allows for a reduction in fluoroscopic time during the procedure. With the patient in position prior to surgery, anteroposterior and lateral fluoroscopic views of the pertinent spinal anatomy are obtained. This is done with a customized reference frame attached to the C-arm or to the patient. This frame serves to superimpose a specific

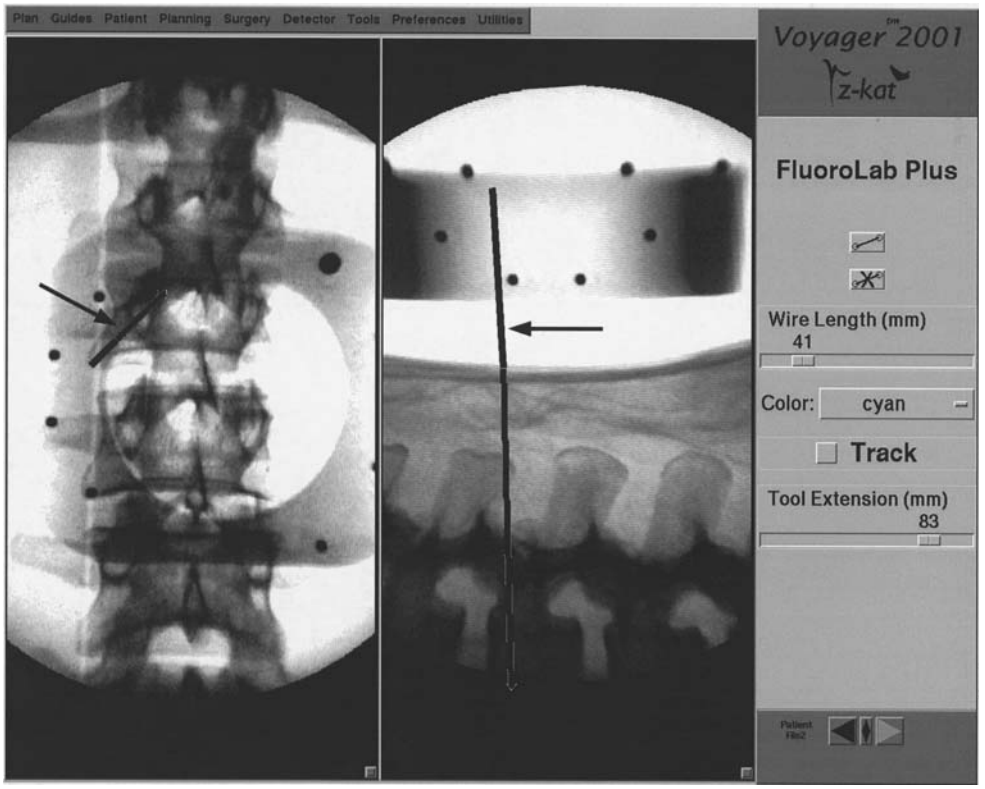

Fig. 2.12 Workstation screen of a fluoroscopic navigational system. Only the standard AP and lateral views are provided. Unlike CT based image-guided navigation, fluoroscopic navigation does not provide the critical axial plane view

grid on the two images obtained. The navigational workstation can then take the two images and relate the spatial position of the imaged anatomy to a navigational probe. A navigational trajectory line and cursor can then be superimposed on the lateral and anteroposterior images, respectively. As the probe is moved over the exposed spinal anatomy during surgery, the trajectory line and cursor will adjust their position on the stationary fluoroscopic images (Fig. 2.12).

Despite the advantages of fluoroscopic navigation, it still has some of the same difficulties that are experienced with standard fluoroscopy. While the radiation dosage to the patient and surgical team is reduced, it is still a factor. Positioning difficulties are the same in the upper thoracic region. Both the upper thoracic region as well as the lumbosacral region in obese individuals can be difficult to adequately visualize with fluoroscopic imaging.

The main disadvantage of fluoroscopic navigation compared to CT-based navigation is the image plane limitation. As with conventional fluoroscopy, fluoroscopic navigation provides the surgeon with only anteroposterior and lateral planar images. Unlike CT-based navigation, it does not provide an axial image, which, in most spinal screw fixation procedures, is the critical plane to identify intrusion into the spinal canal by a medially displaced screw.

A variation of conventional fluoroscopy, isocentric fluoroscopy, offers some improvements to the limitations of fluoroscopic navigation. This device acquires images intraoperatively by rotating the C-arm in a 180° arc around the patient. As with conventional CT imaging, the acquired images can then be reconstructed into multiplanar images, including images in the axial plane. While the images are not of the same quality as standard CT imaging, they are sufficient for navigational use. Image acquisition can also be repeated during surgery if needed to assess the adequacy of decompression or screw positioning.

The most recent advancement in intraoperative imaging involves the use of a flat-panel detector technology to improve intraoperative image acquisition and quality. A flat-panel detector can be mounted onto a mobile imaging unit similar to a conventional C-arm fluoroscope. While this unit can be used to acquire standard anteroposterior and lateral images, its C-arm configuration can be "closed" to completely encircle the patient. This allows the flat-panel detector to be swept in a 360° arc around the patient, significantly improving the acquired image quality. The reformatted images are similar in quality to conventional CT imaging and superior to isocentric C-arm imaging. This ability to acquire high-quality planar images in addition to reformatted

CT images makes this technology ideal for minimally invasive spinal surgery.

Conclusion

Image-guided navigational technology has been successfully applied to spinal surgery. It can be used for both conventional as well as minimally invasive spinal procedures. By linking digitized image data to spinal surface anatomy, image-guided spinal navigation facilitates the surgeon's orientation to unexposed spinal structures, improving the precision and accuracy of the surgery. It is typically used to optimize the placement of spinal fixation screws and to monitor the extent of complex decompressive procedures. It can also be used as a preoperative planning tool.

While image-guided spinal navigation is a versatile and effective technology, it is not a replacement for the surgeon's having a thorough knowledge of the pertinent spinal anatomy as well as correct surgical techniques. It merely serves as an additional source of information used by the surgeon to make selected intraoperative decisions. In this way, it is similar to more conventional intraoperative imaging techniques (i.e., fluoroscopy) except that it provides a greater degree of image information to the surgeon.

Ideally, the clinical application of this technology to spinal surgery should facilitate a reduction in operative time, morbidity, and costs. It should be capable of minimizing or eliminating the need for conventional intraoperative imaging. It should be fast, easy to use, reliable, and capable of providing accurate intraoperative information while minimizing any disruption to the standard routine of each surgical procedure. Ultimately, it needs to be clinically versatile. The routine use of this technology by multiple surgical specialties will drive its continued evolution and development as well as establish it as a cost-effective surgical tool.

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Anterior Cervical Foraminotomy

3

David H. Jho and Hae-Dong Jho

Introduction

The direct removal of compressive pathology while preserving the segmental motion has been a challenge in the surgical treatment of cervical radiculopathy or myelopathy. A classic anterior cervical approach for simple disc herniation or spondylotic stenosis involves surgical decompression followed by fusion using bone graft, often with metal implant. Although this procedure of anterior cervical discectomy with fusion can provide direct elimination of the compressive pathology, it also results in the loss of motion segments by spinal fusion. In attempts to maintain the segmental motion, disc arthroplasty has been recently introduced to the anterior approach. A classic posterior approach usually involves cervical laminectomy or laminoplasty, sometimes accompanied by foraminotomy. However, posterior approaches fail to accomplish the direct removal of compressive pathology that is usually located ventral to the compressed nerve root or spinal cord. Thus, spinal fusion has also been advocated in posterior approaches in order to eliminate dynamic factors. As cervical spine surgery evolved over the decades, H. D. Jho first reported anterior cervical foraminotomy in 1996 under the minimally invasive concept of "functional spine surgery" in which the compressive pathology is directly removed via an anterior approach while the remaining disc and the functioning motion unit is preserved without the use of implants [1].

The originally reported technique for anterior cervical foraminotomy involved the removal of the lateral part of the intervertebral disc known as the uncovertebral juncture. Then several variations of the surgical technique gradually evolved to achieve surgical goals more efficiently while minimizing the surgical impact to the spinal column and functioning motion unit. Unfortunately, no terminology currently exists to describe the evolution of surgical techniques that develops as scientific knowledge and artistic technical advancement improve a particular surgical treatment for a specific condition. The term "surgiology" may be coined to represent this process of surgical evolution and the progressive pursuit of scientific or artistic knowledge to improve a particular operative treatment. The loose derivation of this term is from roots defined by *Webster's Dictionary*, with "surgery" being (a) the treatment of disease, injury, or deformity by manual or instrumental operations, as the removal of diseased parts or tissue by cutting, (b) an operation of this kind, (c) the branch of medicine dealing with this; and the suffix "-ology" as the science, doctrine, or theory of. Surgiology has historically been an inherent process with the tendency to result in the eventual elimination of ineffective surgeries and the improvement of effective techniques.

In this chapter, we describe the surgiology for anterior cervical foraminotomy from its initial description to its technical variations. In the original report, the approach to the nerve root was made through a surgical entry hole at the lateral portion of the uncovertebral juncture. In order to minimize the risk of vertebral artery injury, this approach started with the creation of a small hole at the medial portion of the uncovertebral juncture and was advanced toward the lateral portion of the uncovertebral juncture up to the medial margin of the vertebral artery. This medial-to-lateral bone removal soon evolved to a lateral-to-medial approach with bone removal starting just medial to the vertebral artery. Variations on this technique evolved from the concept that the trajectory from the skin incision to the surgical target in the sagittal plane of the cervical spine directs where a bone opening should be made in order to access the target pathology efficiently and effectively. Thus, the surgical technique became tailored depending on the trajectory, as determined by the nature of

D.H. Jho (✉)
Department of Neurosurgery, Harvard Medical School,
Massachusetts General Hospital, Boston MA, 02114, USA
e-mail: davidjho@gmail.com

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the pathology and cervical anatomy. The surgiologic result was the progressive development of the following modifications: (1) Lower-Vertebral Transcorporeal Approach; (2) Transuncal Approach; (3) Upper-Vertebral Transcorporeal Approach; and (4) Anterior Cervical Foraminoplasty. Details of these surgical techniques will be described in this chapter. The terminology of "rostral-caudal" will be used interchangeably with "upper-lower" or "superior-inferior" when referencing the vertebral bodies bordering the level of target pathology.

Surgical Indications and Preparation

Surgical indications were the same as those for conventional anterior cervical discectomy or corpectomy, with patients often presenting for an alternative surgical option after hearing a recommendation of conventional anterior fusion surgery or posterior approaches. Conservative treatment for a minimum of six weeks was first attempted unless profound motor weakness or significant myelopathy was evident. The initial use of anterior cervical foraminotomy was limited to cervical radiculopathy caused by soft disc herniation or stenosis with bone spur formation. Then the application of the technique and its evolved variations were expanded to decompression of the spinal cord for spondylotic stenosis, ossification of the posterior longitudinal ligament (OPLL), removal of spinal tumors (extradural or intradural), and syringosubarachnoid shunt placement. All patients had preoperative magnetic resonance (MR) scans, with occasional patients requiring myelo-computed tomography (CT) scans, particularly when MR scans showed a surgical artifact from their previous surgery with anterior fusion and metal implant. Intraoperative somatosensory evoked potential (SSEP) monitoring was used in all patients. All patients were kept one night in the hospital as standard protocol, except for the earliest patients, who received surgery on an outpatient basis, and those who insisted on going home on the same day of surgery. All patients obtained follow-up MR scans and dynamic cervical spine roentgenograms six weeks postoperatively.

Surgical Technique

Most of the equipment and instruments are similar to those used in conventional cervical spine surgery. The operation is performed under the operating microscope or an endoscope. A thin-bladed cervical retractor system is used to keep the split longus colli muscle apart in order to expose the uncovertebral juncture. Bone removal is carried out with a 2-mm cutting bit of a slender, high-speed drill. A special curette system was developed in order to undercut bone spurs off the spinal cord posterior to the vertebral body.

Positioning

All operations are performed under general endotracheal anesthesia. Baseline SSEP waveforms are obtained before positioning the head and continuously followed until the end of surgery. Patient positioning is similar to that of conventional anterior discectomy, keeping the head straight (without turning) and the neck neutral (without extension). Gentle neck extension with a small bolster under the shoulders may only be done if sufficient spinal canal is demonstrated on MR scans to provide room for the spinal cord. Precaution during neck positioning is important to prevent position-induced injury to the cervical cord, especially if patients experience exaggerated symptoms by neck extension preoperatively or when severe spinal cord compression is noted in MR scans.

Original Description of Anterior Cervical Foraminotomy

The original technique for anterior cervical microforaminotomy was reported in 1996 [1]. The skin incision site is judged by finger palpation of the C6 transverse tubercle, which is typically palpable just medial to the sternocleidomastoid (SCM) muscle. The skin incision starts 1 or 2 cm lateral from the midline and extends laterally across the medial margin of the SCM muscle for approximately 3–5 cm in total length. Although the center of surgical exposure is usually 3–4 cm lateral from the midline, it must be adjusted to the size of the neck. Patients with a large neck require a longer skin incision in order to maintain a 20° lateral-to-medial trajectory angle toward the surgical target. At the anterior cervical spine, the surgical target anatomy is the uncovertebral juncture, which is covered by the longus colli muscle. Depicted in axial view, the surgical trajectory angle is determined by an extension line from the very medial margin of the inlet neural foramen to that of the outlet. When this line is extended toward the skin, it is the key exposure point of the skin. The platysma may be split longitudinally along the direction of the muscle fibers or alternatively cut parallel to the skin incision. The medial border of the SCM must then be defined, with clean dissection carried down to the prevertebral fascia just medial to the SCM.

The carotid artery on the working side is identified with finger palpation, and a Myerding retractor is placed just medial to the carotid artery. The tracheo-esophageal structure is slightly and gently displaced medially and held with a Meyerding retractor, although not as much exposure of the anterior cervical column is needed as in conventional anterior cervical discectomy. The perimeter of exposure at the lateral portion of the cervical column is just over the longus colli muscle. For upper cervical spine surgery, intraoperative roentgenogram (X-ray) is often obtained to corroborate the correct level of surgery. However, for lower cervical spine surgery, finger palpation of the surgical anatomy at the anterior column of the cervical spine and C6 transverse tubercle is often sufficient for the identification of the correct level of surgery (although confirmatory X-ray may still be done). By palpating the transverse tubercles, the extent of the longus colli is identified. At this point, the operating microscope or endoscope is applied for better visualization and magnification. Endoscopic surgery has been performed for this operation; however, a specially designed endoscope is necessary. The longus colli is split just medial to the transverse tubercles rostral and caudal to the intervertebral disc level. A cervical retractor system is applied between the split longus colli muscle fibers in order to maintain exposure of the uncovertebral juncture. The original description mentioned sectioning of the medial part of the longus colli muscle, but this soon evolved to splitting the longus colli muscle, allowing its preservation. With microdissection just lateral to the uncinate process, the vertebral artery is defined. Then the proximal transverse processes of the rostral and caudal vertebrae are defined. The vertebral artery pulsation is often visible lateral to the uncinate process. In the original description, the lateral 5- to 8-mm portion of the uncovertebral juncture was drilled and removed, which eventually evolved into less bone removal. The vertical dimension of bone removal was originally from the inferior margin of the rostral vertebra's medial transverse process to the superior margin of the caudal vertebra's medial transverse process, usually measuring 7–10 mm in total length. Bone removal is performed using a 2-mm cutting bit in a slender, high-speed drill. Opening of the posterior longitudinal ligament (PLL) is usually done in order to confirm an adequate decompression from the lateral portion of the spinal cord to the nerve exit behind the vertebral artery. It is possible for venous bleeding to be cumbersome while the PLL is open. The intervertebral disc is kept largely intact. Once adequate decompression has been accomplished, the platysma and subcutaneous tissue are closed with 3–0 absorbable sutures. The surgical incision site is infiltrated with a local anesthetic, and the skin is closed with absorbable stitches or adhesive glue.

The original technique involved the removal of a few millimeters' width of the most lateral portion of the uncovertebral juncture in a medial-to-lateral direction as a surgical conduit to the compressive pathology. However, this technique was soon modified because the end result of bony removal often became more excessive than required since concern for potential vertebral artery injury frequently made the start of bone removal further medial than truly necessary. In addition, the bone opening at the uncovertebral juncture did not always produce an optimal access to the target pathology because the arrival point of the surgical trajectory toward the pathological target is influenced by the skin incision. Thus, technical modifications soon followed.

Surgiologic Evolution of Anterior Cervical Foraminotomy

Lower-Vertebral Transcorporeal Approach

The term "lower-vertebral transcorporeal approach" refers to the location of the bone opening at the lateral portion of the lower vertebra to the intervertebral disc. For a C3-4 operation or when a skin incision is made inadvertently more caudal than it should be at any cervical disc level, this technique is required. The medial portions of the transverse processes at the rostral and caudal vertebrae are identified. The superomedial 1- to 2-mm portion of the transverse process at the lower vertebra is removed, and the vertebral artery is identified. Just medial to the vertebral artery, the superolateral 2- to 3-mm portion of the lower vertebra is drilled away posteriorly using a 2-mm cutting drill bit [Figs. 3.1(a), (b)]. The total vertical dimension of the bone removal is approximately 5 mm in length. A cephalad-directed surgical trajectory will lead the drilling posteriorly toward the target [Fig. 3.1(c)]. In other words, a superior-posterior surgical trajectory from a bone opening at the rostral lower vertebral body leads to the compressing pathology at the intervertebral disc while preserving the uncovertebral juncture at the ventral part of the cervical spine. Microdissectors and various curved-up curettes are used to remove compressing herniated soft disc or bone spurs. The nerve root and the most lateral portion of the spinal cord are released from compression.

The amount of bone removal posteriorly must be tailored depending on the extent of the pathology. As drilling is advanced posteriorly, the surgical reference points include the endplate of the lower vertebra, followed by the intervertebral disc space, and the endplate of the upper vertebra at the area of target pathology. The PLL is first

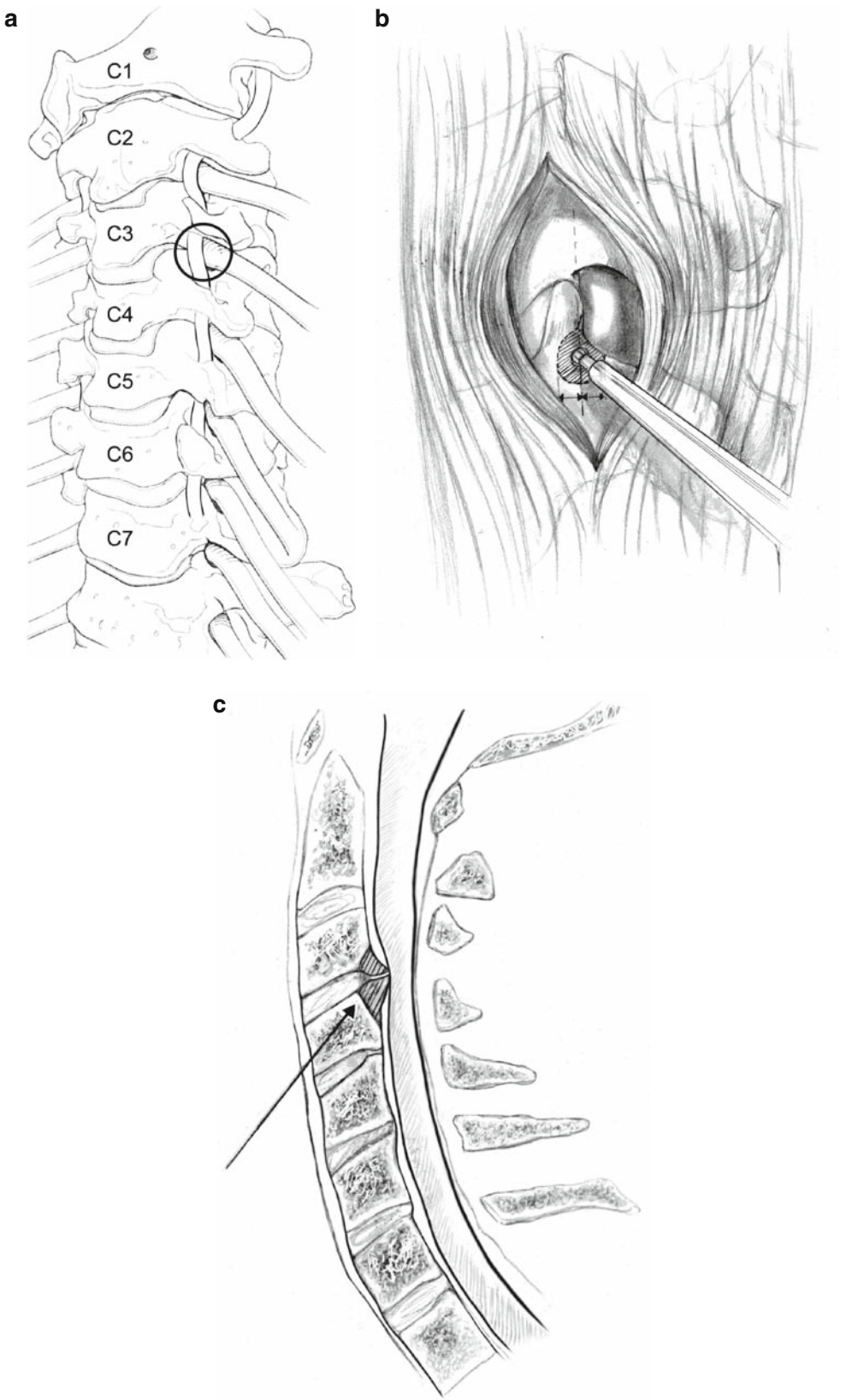

Fig. 3.1 The schematic drawing demonstrates the lower-vertebral transcorporeal approach from the left side. (**a**) The *circled area* is a focal area on which this anterior foraminotomy is performed. A small bone opening is made at the superolateral aspect of the lower vertebra. The most medial 2-mm portion of the transverse process at the lower vertebra is removed, and the vertebral artery is exposed. (**b**) Then the lateral 3-mm portion of the superolateral part of the lower vertebra or the base of the uncinate process (*dotted area*) is drilled toward the posterior longitudinal ligament. This technique is utilized when a foraminotomy is performed at a high cervical disc such as C3-4. (**c**) The anteroposterior surgical trajectory from the skin incision to the surgical target pathology makes a cephalad incline as demonstrated in a drawing. Thus, the bone opening has to be made at the lower vertebra in order to reach the target along the surgical trajectory. Similar techniques can be used if a skin incision is made inadvertently caudal for surgery at other cervical levels

exposed at the uncompressed portion just caudal to the compressing pathology and then exposed rostral to the compressing pathology. Drilling must be done with caution at the lateral portion where the nerve root is located. The thin cortical bone covering the nerve root is dissected and removed, followed by lifting the compressing pathology away from the PLL and removing it. The PLL can be opened medially with a microdissector and excised laterally except when the MR scans do not suggest soft disc herniation and the PLL fails to show any defect, in which case the PLL may not be removed. Removal of the PLL can cause cumbersome epidural bleeding since the epidural veins run between the two layers of the PLL at the lateral spinal cord canal. The spinal cord dura mater is identified, and when spinal cord decompression is required, the compressing pathology is removed further medially along the posterior margin of the rostral and caudal vertebrae.

Transuncal Approach

When the surgical trajectory from the skin incision to the target pathology is perpendicular to the sagittal plane of the cervical spine, a bone opening at the anterolateral spine must be made along this trajectory line. Particularly for C4-5 or C5-6 operations, a routine skin incision at the upper or mid-portion of the neck will produce such a perpendicular surgical trajectory. In this case, the uncinate process lies along the perpendicular surgical trajectory [Figs. 3.2(a)–(c)]. The skin incision to the point of bone exposure is similar to the general description of the anterior cervical foraminotomy approach. The most medial 1- to 2-mm portions of the transverse processes of both upper and lower vertebrae are removed, and the vertebral artery is identified. The lateral uncinate process is dissected from the vertebral artery, and the most lateral 2- to 3-mm portion of the uncinate is drilled just medial to the vertebral artery toward the PLL. The compressing pathology has to be exposed from the normal margin of the rostral vertebra to the normal margin of the caudal vertebra. The caudal-to-rostral exposure must be performed in reference to the endplates of the caudal and rostral vertebrae along with the intervertebral disc space posteriorly. The vertical extent of the bone removal is usually about 5 mm in length. Once the PLL has been exposed, excision is performed for compressing pathology such as herniated soft disc or bone spurs. Often the PLL is opened to expose the dura mater at the most lateral portion of the spinal cord and proximal nerve root in order to detect any hidden migrated disc fragments. Awareness is necessary to avoid damaging the thin bony wall of the medial uncinate in order to maintain the integrity of the intervertebral disc. When spinal cord decompression is required, a specially designed curette system is used to achieve further medial decompression by undercutting the compressive pathology posterior to the rostral and caudal vertebral bodies. Surgical closure is made using the aforementioned techniques.

Upper-Vertebral Transcorporeal Approach

This technique involves creating a bone opening at the inferolateral portion of the upper vertebra when the anterior-posterior surgical trajectory inclines caudally [Figs. 3.3(a)–(c)]. This approach is most often used in C6-7 or C7-T1 surgery but is also commonly used with other levels by making the skin incision purposefully cephalad. The vertebral artery is exposed with removal of a 2-mm medial portion of the transverse process at the upper vertebra. A bone opening is then made at the inferolateral 2- to 3-mm portion of the upper vertebra with drilling toward the PLL. The surgical trajectory is directed toward the pathological target through only the most posterior portion of the intervertebral endplate. Damage to the intervertebral endplate at the anterior two-third portion of the intervertebral disc must be avoided. The rest of the procedure is the same as described for other approaches.

Anterior Cervical Foraminoplasty

Sometimes the compressive pathology continues along the entire medial wall of the narrowed neural foramen, such as when spondylotic bone spur formation extends from the inlet (where the nerve originates from the spinal cord) to the outlet (where the nerve exits posterior to the vertebral artery). In this case, the nerve foramen must be enlarged along its longitudinal axis. The term "foraminoplasty" describes this procedure of remodeling the neural foramen to its larger normal shape by the elimination of medial bone spurs along the longitudinal axis of the neural foramen (Fig. 3.4). Since the compressive pathology usually exists at the medial wall of the neural foramen, an anterior approach toward the medial wall of the foramen is most suitable for effectively eliminating the compressive pathology.

The 2-mm medial portion of the transverse process at the vertebral artery foramen is removed at the upper and lower vertebrae. Then the inferolateral portion of the upper vertebra, the superolateral portion of the lower vertebra, and the lateral 2-mm portion of the uncinate process are drilled toward the PLL. Drilling has to be directed along the nerve passage from pedicle to pedicle in order to have complete decompression in the vertical

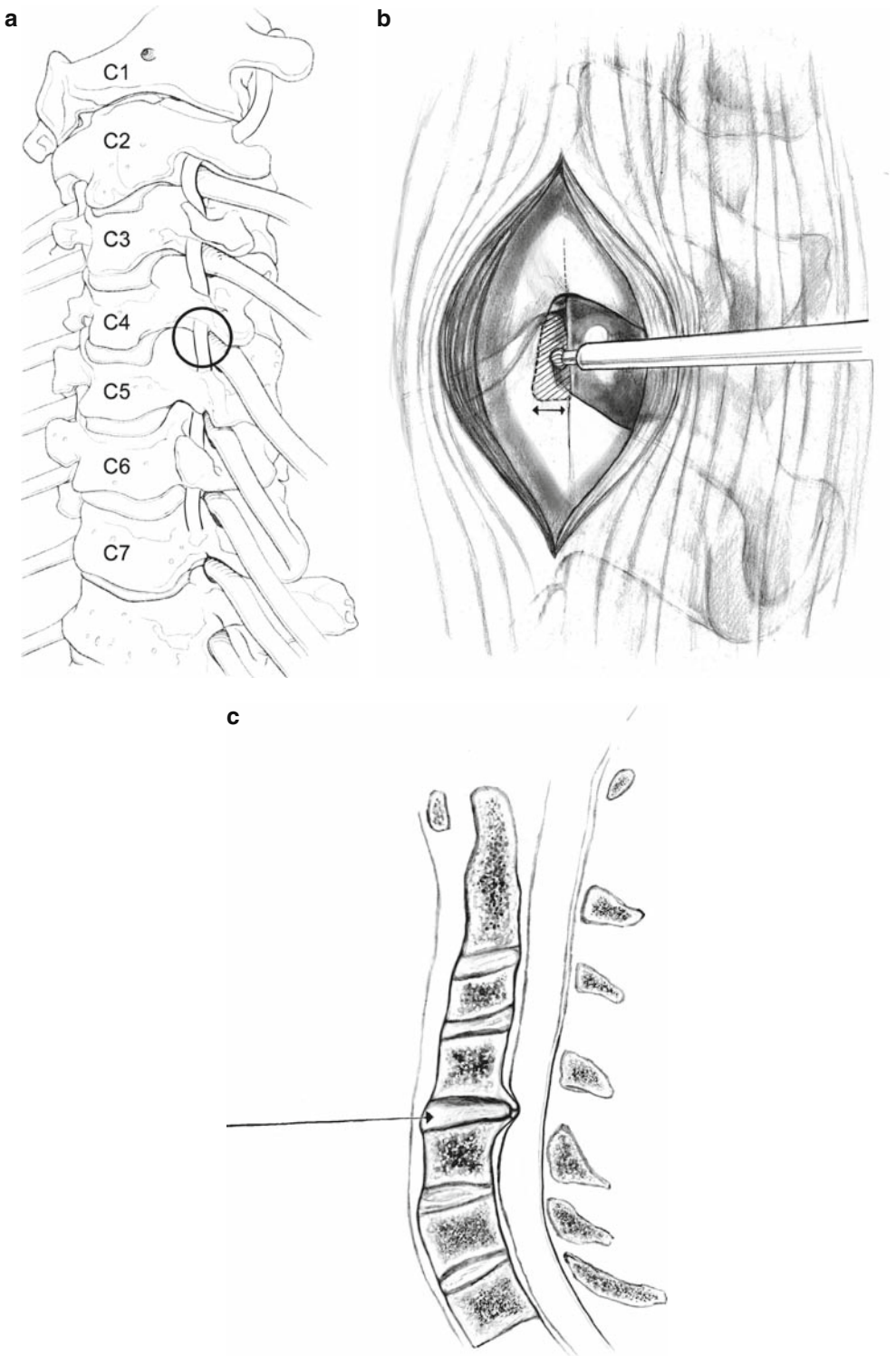

Fig. 3.2 The schematic drawing illustrates the transuncal approach from the *left side*. (**a**) The *circled area* indicates the surgical area at C4-5. The medial 2-mm portion of the upper and lower transverse process is removed, and the vertebral artery is defined. The lateral uncinate process is dissected from the vertebral artery, and the lateral 2- to 3-mm portion of the uncinate process (*dotted area*) is drilled toward the posterior longitudinal ligament. (**b**) The thin layer of the medial uncinate process has to be preserved in order to maintain the integrity of the intervertebral disc. (**c**) The surgical trajectory from the skin incision to the target pathology must be perpendicular to the longitudinal axis of the spine for this technique

dimension. After the PLL has been exposed, posterior bone spurs are excised in front of the lateral spinal cord. If spinal cord decompression is required, bone spurs anterior to the spinal cord are excised through a foraminoplasty hole. The PLL is excised, and the dura mater is exposed from pedicle to pedicle. Sometimes it is necessary to shave the superior portion of the inferior pedicle when the vertical dimension of the neural foramen is narrow, which is relatively common in elderly patients. Surgical closure is the same as previously described.

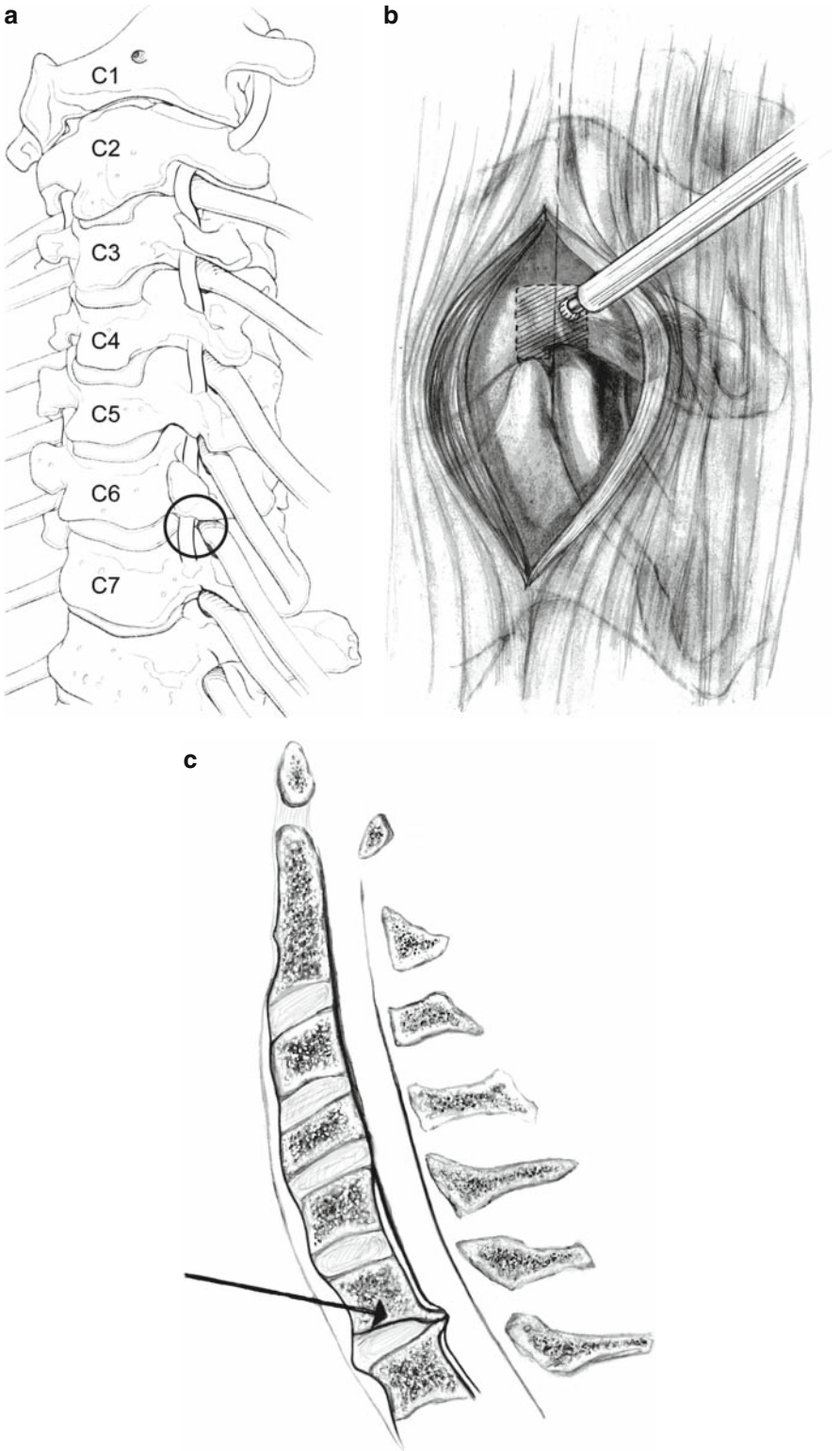

Fig. 3.3 The drawings reveal the area of interest by (**a**) a *circle*, (**b**) a bone opening, and (**c**) a surgical trajectory in the upper-vertebral transcorporeal approach from the left side. The medial 2-mm portion of the transverse process at the upper vertebra is removed, and the vertebral artery is defined. The lateral 3-mm portion of the inferolateral upper vertebra is drilled posteriorly (*dotted area*). The anterior two thirds of the endplate should avoid damage in this technique. An anteroposterior surgical trajectory from the skin incision to the target pathology inclines caudally in this technique. This technique has been most commonly used for radiculopathy

Postoperative Management

Postoperatively, all patients were kept overnight in the hospital as standard protocol except for the earliest described patients (who received outpatient surgery) and some patients who insisted on going home on the same day of surgery. Postoperative pain is relatively minor, and most patients are prescribed oral narcotic analgesics, although some decline to take them. Patients are allowed to resume normal routine activities immediately following

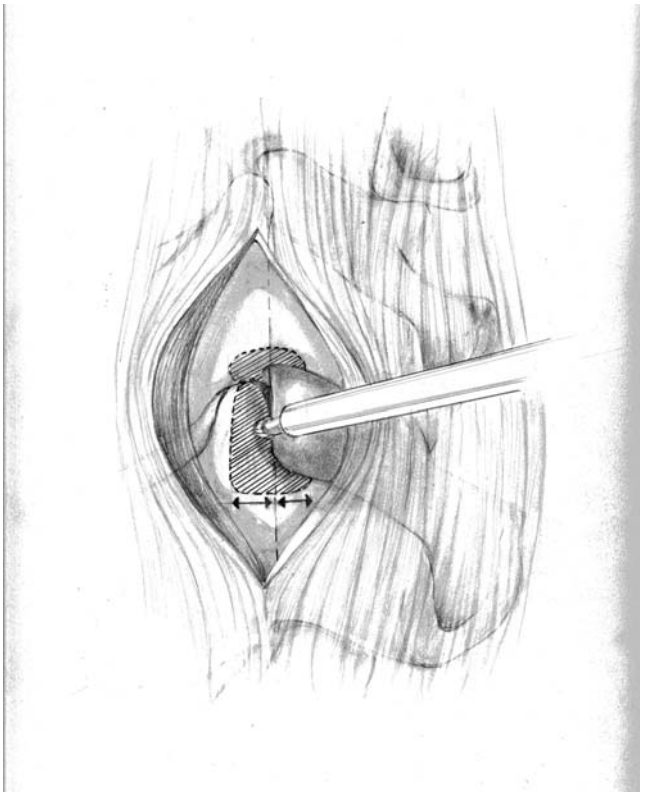

Fig. 3.4 The schematic drawing demonstrates anterior cervical foraminoplasty. The vertebral artery is defined by the removal of a 2-mm portion of the transverse processes at the upper and lower vertebrae. This technique is used for spondylotic foraminal stenosis. The bone spurs along the medial wall of the neural foramen along the longitudinal axis of the neural foramen are trimmed with a high-speed drill

surgery. Cervical collars are neither necessary nor used. The surgical wound is exposed to the air the following day, and exercises or taking a shower are allowed the following day. Contact sports activities and heavy weightlifting are delayed for four to six weeks. Return to office-type work is allowed within a few days, but return to physically laborious jobs is not allowed for four to six weeks. All obtained postoperative contrast-enhanced MR scans and dynamic roentgenogram six weeks postoperatively as routine protocol.

Results

We previously reported our series of 104 patients who met the following study criteria: unilateral cervical radiculopathy that had not responded to conservative treatment after at least six weeks (or at least four weeks if patients exhibited profound motor weakness), imaging studies confirming pathoanatomic features corresponding to the clinical symptoms, no previous cervical spine surgery, and no significant spondylotic stenosis causing spinal cord compression. Forty-five patients were men, and 59 were women. Patient ages ranged from 26 to 74 years, with the median age being 46 years. The compressive pathology was spondylotic spurs in 44 patients (42.3%), soft disc herniation in 54 patients (51.9%), and a combination of the two in six patients (5.8%). The duration of symptoms ranged from four weeks to 156 months (mean 17.6 months). Follow-up periods ranged from 12 to 86 months (median 36 months). In addition to radiculopathy, preoperative symptoms included severe neck pain in 83 patients (79.8%) and significant occipital head pain in 11 patients (10.6%). Surgical results were graded as follows: "excellent," patient exhibited complete resolution of all symptoms; "good," patient experienced relief of radiculopathy but still experienced occasional minimal/mild residual nonradicular discomfort; "fair," patient exhibited mild residual radiculopathy with or without mild/moderate residual nonradicular discomfort; or "poor," patient continued to exhibit significant radicular symptoms with or without nonradicular discomfort (including those unchanged or worse than preoperative condition). Among 104 patients, 83 patients (79.8%) demonstrated excellent results, 20 patients (19.2%) demonstrated good results, and one patient (1%) experienced a fair outcome. No patient had a poor outcome, and there were no results that were unchanged or worse. One patient developed discitis, which resulted in spontaneous fusion at the operated level following antibiotic treatment, although his radiculopathy resolved well. One patient developed transient position-related hemiparesis, which resolved in six weeks. Two patients developed transient Horner's syndrome, which resolved six weeks postoperatively [2].

Discussion

Although variations in surgical trajectories to the cervical spine such as lateral approaches have been reported, the notion of discectomy with bone fusion was retained [3–6]. Conventional anterior cervical disc surgery evolved over a half-century into the complete removal of the intervertebral disc with bone graft fusion and metal implant by adhering to this idea [7]. The more recent methods using arthroplasty with artificial discs attempt to reestablish the motion segment but still rely on discectomy. The original description of

anterior cervical foraminotomy involved not only new surgical techniques utilizing access via an anterolateral route through the uncovertebral juncture but introduced the novel concept of "functional spine surgery" [1]. This goal of "functional spine surgery" entailed preserving the motion unit while achieving the direct removal of the compressive pathology. The original description involved the removal of the most lateral 5-mm portion of the uncovertebral juncture as a surgical access to the compressive pathology, followed by wide decompression of the nerve root from its origin at the spinal cord to its exit posterior to the vertebral artery. The evolution of our surgical techniques has been reported [2, 8–17].

Generally, the intervertebral discs of the cervical spine in the sagittal plane incline cephalad from an anterior-to-posterior direction. Therefore, the surgical approach involved in the originally described foraminotomy usually arrives at the superior portion of the pedicle and inferior portion of the surgical target. In order to compensate, the surgical trajectory must be inclined cephalad while proceeding posteriorly. The skin opening also has to line up with the surgical trajectory of this foraminotomy. Thus, the skin incision has to be made much more cephalad than in conventional anterior discectomy, and the anterior bone opening is also shifted cephalad to arrive at the surgical target efficiently. The anterior bone opening is made at the most lateral portion of the upper vertebral body to arrive at the surgical target naturally when the foraminotomy hole is advanced posteriorly perpendicular to the longitudinal axis of the spinal column. The posterior one-third portion of the anteroposterior surgical trajectory involves the intervertebral juncture, which is the posterior portion of the uncovertebral juncture and usually comprises the actual compressive pathology. This technique consists of a bone opening at the upper vertebra; thus, the technique is termed a "upper-vertebral transcorporeal approach." When an anteroposterior surgical trajectory is perpendicular to the longitudinal axis of the spine, the bone opening has to be made at the lateral portion of the uncinate; hence, the variant technique is called a "transuncal approach." When the surgical trajectory inclines cephalad, a "lower-vertebral transcorporeal approach" has to be adopted with a bone opening made at the lateral lower vertebrae. The medial 2-mm portion of the vertebral artery is exposed in order to minimize the amount of bone removal at the vertebral body. When a narrowed neural foramen requires reconstruction into a larger normal shape, "anterior foraminoplasty" is performed with the direct removal of the medial bone spurs along the longitudinal axis of the neural foramen. Others have also reported their own experiences with anterior cervical foraminotomy [18–20].

Although the surgical risks of anterior cervical foraminotomy have been minimal in our experience, permanent and serious complications theoretically exist as in any type of anterior cervical spine surgery. Major potential concerns include Horner's syndrome, vertebral artery injury, recurrent disc herniation, and spinal instability. Since the cervical sympathetic nerve and chain pass along the lateral margin of the longus colli, Horner's syndrome can occur if sympathetic nerves are damaged by traction injury or complete section while dissecting the longus colli. Depending on the method and extent of injury, Horner's syndrome can be temporary or permanent. Vertebral artery injury is a risk in any situation but is a particular concern in anatomic variations in which the vertebral artery enters the transverse foramen through C4 or C5 instead of the common location at C6. When the lateral aspect of the cervical spine is exposed by splitting or dissecting the longus colli, the vertebral artery that is passing through the muscle can be injured. The level of vertebral artery entry into the transverse foramen should be foreseen on preoperative MR scan in order to help avoid this injury. As vertebral artery injury can result in brainstem stroke immediately or in a delayed fashion, damage may be repaired surgically with the aid of extended proximal and distal exposure. Recurrent disc herniation through the surgical defect in the annulus is a delayed complication that can occur when the intervertebral disc is violated substantially. In order to prevent recurrent disc herniation, the foraminotomy hole has to be minimal in size but large enough to provide adequate decompression. Spinal instability may also occur if bone removal is substantial [19]. When patients complain of significant neck pain postoperatively, spinal instability has to be considered. When patients have significant spinal instability, fusion may be necessary. Other possible complications associated with conventional anterior cervical spine surgery are also relevant such as cerebrospinal fluid leakage, epidural bleeding or hematoma, nerve root or spinal cord damage, wrong-level operation, infection, or wound hematoma. Hoarseness can theoretically occur as it does after conventional anterior cervical spine surgery, but it is very unlikely since the anterior foraminotomy technique is further lateral in approach. This surgery is not recommendable to an inexperienced surgeon due to these potential complications unless a surgeon is well-trained or experienced in this particular type of surgery.

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Posterior Cervical Foraminotomy and Laminectomy

4

John E. O'Toole, Kurt M. Eichholz, and Richard G. Fessler

Introduction

Posterior decompressive procedures are fundamental tools in the surgical treatment of symptomatic cervical degenerative spine disease [1–4]. Even as anterior cervical procedures have gained prominence, posterior cervical laminoforaminotomy still provides symptomatic relief in 92–97% of patients with radiculopathy from foraminal stenosis or lateral herniated discs [3, 5]. Similarly, posterior cervical decompression for cervical stenosis achieves neurological improvement in 62.5–83% of myelopathic patients undergoing either laminectomy or laminoplasty [4, 6–8]. Moreover, these operations avoid the complications attendant to anterior approaches to the cervical spine, namely, esophageal injury, vascular injury, recurrent laryngeal nerve paralysis, dysphagia, and accelerated degeneration of adjacent motion segments after fusion [9–11].

However, open posterior approaches to the cervical spine require extensive subperiosteal stripping of the paraspinal musculature, which leads to postoperative pain, spasm, and dysfunction and can be persistently disabling in 18–60% of patients [4, 9, 12, 13]. Furthermore, the preoperative loss of lordosis and long-segment decompressions increase the risk for postoperative sagittal plane deformity [14–17], a complication that frequently prompts instrumented arthrodesis at the time of laminectomy. Employing these extensive posterior fusion techniques increases operative risks, time, and blood loss; exacerbates early postoperative pain; and potentially contributes to adjacent-level degeneration.

The fundamental tenet of minimal access techniques is the reduction of approach-related morbidity. To that end, the advent of muscle-splitting tubular retractor systems and improvements in endoscopic technology and associated instruments have allowed for the application of minimally invasive techniques to posterior cervical decompressive procedures [13, 18]. The microendoscopic cervical foraminotomy/discectomy (CMEF/D) was first described in a cadaver model that demonstrated the ability to achieve at least equal bone removal and nerve root exposure when directly compared to the open technique [19, 20]. The reports of CMEF/D used clinically [9, 13, 21] have demonstrated that efficacy is equivalent to open cases (87–97% rate of symptom relief) but that blood loss, length of stay, and postoperative pain medication usage are all reduced in CMEF/D cases. We have recently reviewed clinical outcomes after CMEF/D using validated outcome instruments in a prospective cohort of 30 patients (unpublished data). In these patients, mean Visual Analog Scale (VAS) scores decreased from 2.0 to 0.6 for headache, 5.0 to 2.1 for neck pain, and 4.8 to 1.9 for arm pain. Mean Neck Disability Index scores improved from 37.7 to 20.8, and mean Short Form-36 scores showed statistically significant improvements for bodily pain, physical function, and role physical subscales. The mean operative blood loss was 80 ml, and the mean hospital stay for the cohort was 10 h. When added to the collected literature to date, this data establishes CMEF/D as a safe, effective, minimally invasive outpatient procedure for the treatment of isolated cervical radiculopathy.

The feasibility of minimal access multilevel laminectomy and laminoplasty techniques was also first demonstrated in cadaver models [22, 23]. In separate studies, both techniques demonstrated a 43% expansion of the cross-sectional area of the spinal canal [16, 22, 23]. The clinical application of minimally invasive posterior cervical decompression for stenosis, however, has not been studied as extensively as CMEF/D. The use of minimally invasive cervical laminoplasty has been reported in four patients as technically safe and feasible, with a mean improvement of 1.25 points on the Nurick

J.E. O'Toole (✉)
Department of Neurosurgery, Rush Medical College of Rush University Medical Center, Chicago, IL 60612, USA
e-mail: john_otoole@rush.edu; johneotoole@hotmail.com

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Scale postoperatively [22]. The authors of the minimally invasive laminoplasty studies have noted technical difficulties associated with elevating the lamina and inserting bone grafts.

Cervical microendoscopic decompression of stenosis (CMEDS), on the other hand, is based on more familiar techniques that have already been applied to lumbar stenosis [24]. By preserving much of the normal osteoligamentous anatomy of the cervical spine, the CMEDS procedure reduces the risk for postlaminectomy kyphosis as well as problems associated with the postlaminectomy membrane [4, 16]. Yabuki et al. [25] published their series of 10 patients operated upon for cervical spondylotic myelopathy utilizing the endoscopic METRx system (Medtronic Sofamor Danek, Memphis, TN). Using bilateral dilations and laminotomies to remove dorsal bony and ligamentous compression, they treated up to two levels of stenosis and reported a mean operative time of 164 min, a mean blood loss of 45 ml, and a mean posterior neck VAS scores of 2.8 on postoperative day 1 and 0.8 on postoperative day 3 [25]. Although no control group was presented, the authors anecdotally felt that the decrease in postoperative neck pain compared to open procedures was dramatic. At a mean of 15 months of follow-up, patients had a mean improvement in their Japanese Orthopedic Association score of 2.5 points. They had no complications, postoperative instability, or need for reoperation [25].

In order to preserve the contralateral bony and superficial ligamentous structures and perform only one muscle dilation, we prefer the unilateral approach to CMEDS as described below. Perez-Cruet and the senior author (RGF) have previously reported on five patients undergoing CMEDS at one, two, or three levels [16]. All patients demonstrated an improvement in their myelopathy and returned to work, with the only complication being one unintended durotomy that sealed spontaneously.

Indications

The operative indications for CMEF/D are radiculopathy from lateral disc herniations or foraminal stenosis (single or multilevel) (Fig. 4.1), persistent or recurrent root symptoms following anterior cervical discectomy and fusion, and cervical disc disease in patients for whom anterior approaches are relatively contraindicated (anterior neck infection, tracheostomy, prior irradiation) [13]. The indications for CMEDS are central spondylotic stenosis (e.g., ligamentum flavum or facet hypertrophy) in patients presenting with myelopathy or myeloradiculopathy. The neurological symptoms should correlate with radiographic findings.

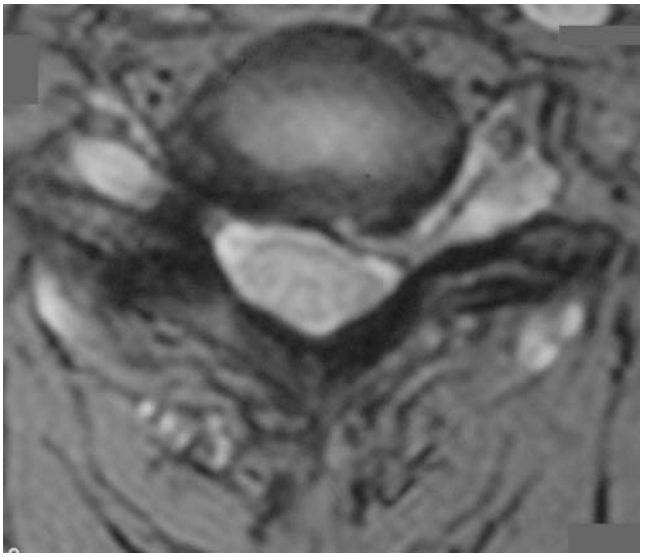

Fig. 4.1 Axial T2-weighted cervical spine MRI demonstrates laterally herniated disc to the left with resultant effacement of the lateral thecal sac and compression of the exiting nerve root

Contraindications include pure axial neck pain without neurological symptoms, gross cervical instability, symptomatic central disc herniation, excessive burden of ventral disease (e.g., diffuse OPLL) or a kyphotic deformity that would make posterior decompression ineffective, or an inability to tolerate general anesthesia.

Preoperative Evaluation

Following a detailed history and physical examination, the preoperative radiographic evaluation should include magnetic resonance imaging (MRI) or postmyelographic computed tomography (CT) to define the pathoanatomy, and anteroposterior (AP), lateral, and dynamic cervical radiographs to rule out instability. Preoperative electromyography (EMG) and nerve conduction studies may also assist in the neurological localization of a specific radiculopathy.

Equipment

Required equipment specific to CMEF/D and CMEDS includes

- Mayfield or other head fixation device compatible with the semisitting position

- Tubular retractor system with compatible endoscope
- Endoscopic camera system with appropriate monitor
- Endoscopic spinal instruments (including microcurettes and 1- and 2-mm rongeurs)
- High-speed drill
- Intraoperative fluoroscopy.

Setup

General endotracheal anesthesia is induced with fiberoptic intubation employed in patients with chronic spinal cord compression. Somatosensory evoked potentials (SSEP) and myotomal EMG are monitored throughout the case. An arterial line is often helpful to maintain normotension with the patient in the sitting position in order to avoid spinal cord hypoperfusion. A precordial Doppler is used to monitor for air embolism, although this has not presented a problem to date. Foley catheterization is generally not needed. Routine perioperative antibiotics are administered as is an intravenous corticosteroid at the surgeon's discretion. Paralytic agents are minimized after induction to allow for physical intraoperative feedback of nerve root irritation. The table is then turned 180° relative to the anesthesia station. The patient is placed in a Mayfield three-point head fixation, and the table progressively flexed and put into Trendelenburg to bring the patient into a semisitting position such that head is flexed but not rotated and the posterior neck is perpendicular to the floor (Fig. 4.2). The sitting position confers the advantages of decreased blood pooling in the operative field, decreased blood loss, decreased operative times, and gravity-dependent positioning of the shoulders for better lateral fluoroscopic images [9, 13]. The Mayfield is secured to a table-mounted cross-bar, and the patient's arms are folded across the lap or chest depending upon the body habitus. The legs, hands, and arms are well padded, particularly over the cubital tunnel, to prevent positional ulnar neuropathy. The base of the fluoroscopic C-arm is placed on the same side as the surgical approach. The fluoroscopic and endoscopic monitors are placed next to the head of the patient, opposite the side of approach, so that the surgeon can look

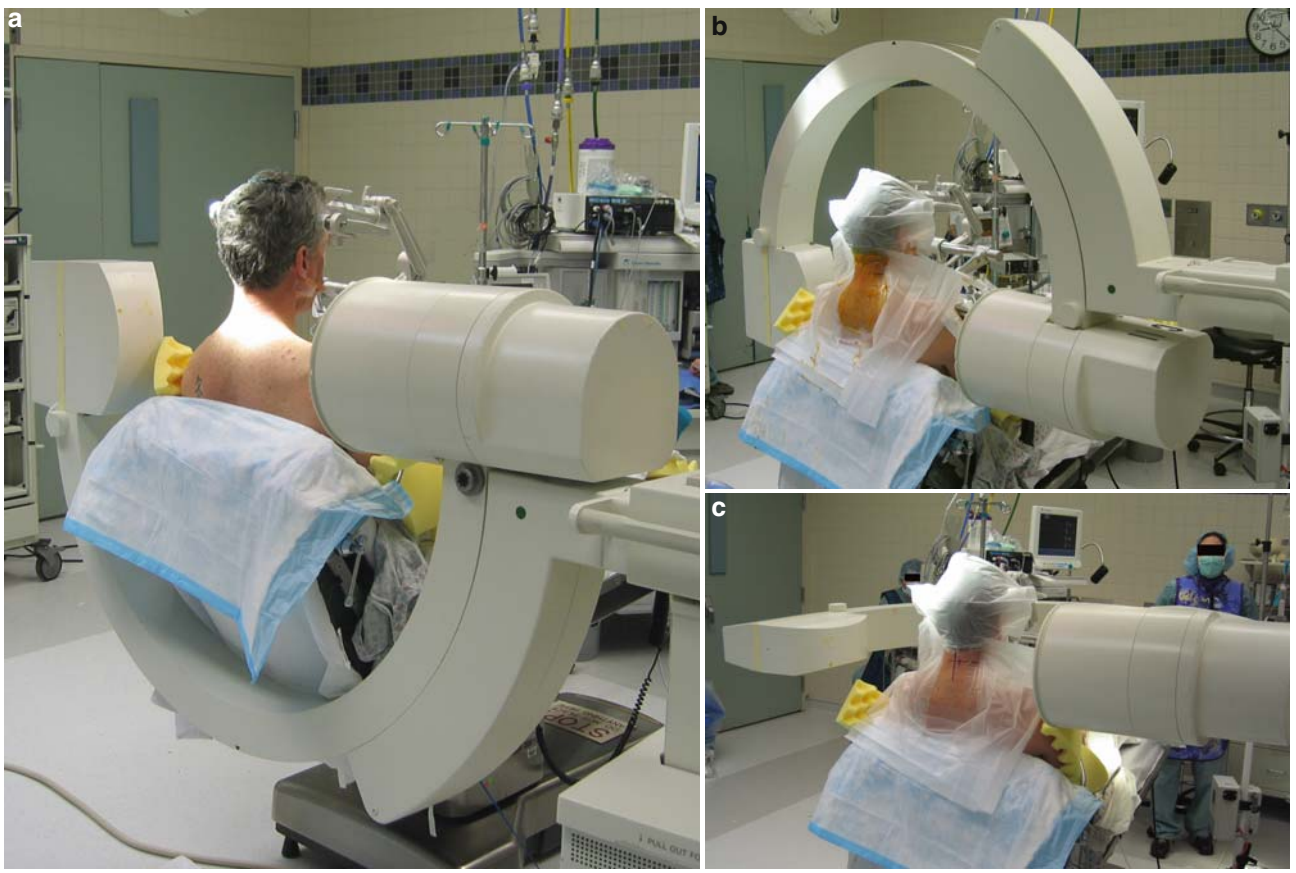

Fig. 4.2 Operative positioning of patient in Mayfield head fixation for CMEF/D or CMEDS with the various positions of the intraoperative fluoroscope C-arm: (**a**) Beneath patient, (**b**) above patient, and (**c**) in front of patient

directly at the monitors while standing behind the patient and operating through the tubular retractor at a comfortable height. The C-arm may be arranged beneath, above, or in front of the patient (Fig. 4.2), depending upon the design specifics of the C-arm and operating table and whether or not AP images will be needed during the case. The neck is checked a final time to ensure safe positioning that allows adequate jugular venous drainage and airway patency.

Technique Description

This section outlines the technique for posterior CMEF/D [5, 9, 13, 18] followed by CMEDS [16, 22, 25]. Although the procedures described here utilize the METRx retractor and endoscope system (Medtronic Sofamor Danek, Memphis, TN), the principles are the same regardless of the retractor system used.

Prior to draping, an initial fluoroscopic image is acquired to confirm adequate visualization and to plan the initial entry point. The posterior neck is shaved, scrubbed, prepared, and draped in the usual manner. It is helpful to use adhesive lined drapes and/or an antibacterial adhesive layer such as Ioban (3 M Health Care, St. Paul, MN) to maintain the orientation and position of the drapes during the procedure. Suction tubing, cautery lines, and endoscope light source and camera cables are typically draped over the top or side of the field and secured against the drapes. The operative level(s) is once again confirmed on lateral fluoroscopy while a long K-wire or Steinman pin is held over the lateral side of the patient's neck. A 1.8-cm longitudinal incision is marked out approximately 1.5 cm off the midline on the operative side, and this is injected with local anesthesia. For two-level procedures, the incision should be placed midway between the targeted levels. For bilateral procedures, a midline skin incision can be used and the skin retracted to each side for independent dilations. After an initial stab incision, the K-wire is advanced slowly though the musculature under fluoroscopic guidance and docked at the inferomedial edge of the rostral lateral mass of the level of interest (Fig. 4.3). It is critical to engage bone and not penetrate the interlaminar space where the laterally thinned ligamentum flavum may not protect against iatrogenic dural or spinal cord injury. At this point, the incision is completed about 1 cm above and below the K-wire entry point and the wire is removed. The axial forces that are applied during muscle dilation in the lumbar spine are more hazardous in the cervical spine. Therefore, the cervical fascia is incised equal to the length of the incision using monopolar cautery or scissors so that muscle dilation can proceed in a safe and controlled fashion. The K-wire is replaced under fluoroscopy again, and the tubular muscle dilators are serially inserted. The final 16- or 18-mm tubular METRx retractor is placed over the dilators and fixed into place over the laminofacet junction with a table-mounted flexible retractor arm, and the dilators are removed (Fig. 4.3). The 25° angled glass-rod endoscope is attached to the camera, white-balanced, and treated with an antifog solution prior to insertion and attachment to the tube via a cylindrical plastic friction-couple (Fig. 4.4).

Monopolar cautery and pituitary rongeurs are used to clear the remaining soft tissue off the lateral mass and lamina of interest, taking care to start the dissection over solid bone laterally (Fig. 4.5). A small up-angled curette is used to gently detach the ligamentum flavum from the undersurface of the inferior edge of the lamina, and a Kerrison punch with a small footplate is used to begin the laminotomy. At this point, the CMEF/D and CMEDS diverge in their course. We describe the technique for CMEF/D first followed by CMEDS.

CMEF/D Technique

The subsequent steps of the operation differ little from the open procedure. Depending upon the degree of facet hypertrophy, the Kerrison may be used to complete most of the laminotomy and early foraminotomy or the drill may be required early in the course of bone removal (Fig. 4.5). The use of a fine cutting bit and adjustable guard sleeve greatly facilitates the use of the drill around critical nervous structures (Fig. 4.6). The ligamentum flavum can be removed medially after the laminotomy to identify the lateral edge of the dura and the proximal portion of the nerve root [Fig. 4.5(c)]. The dorsal bony resection should follow the nerve root into the foramen by removal of part of the medial facet. It is crucial to preserve at least 50% of the facet to maintain biomechanical integrity [26]. This amount of resection permits adequate exposure of the root in the foramen. At this point, the venous plexus overlying the nerve root should be carefully coagulated with bipolar cautery and incised. Fortunately, the use of the sitting position makes blood pooling and obscuring of the operative field less of a concern. With the root well visualized, a fine-angled dissector can be used to palpate ventral to the nerve root for osteophytes or disc fragments. Should an osteophyte be present, a down-angled curette may be used to tamp the material further ventrally into the disc space or fragment it for subsequent

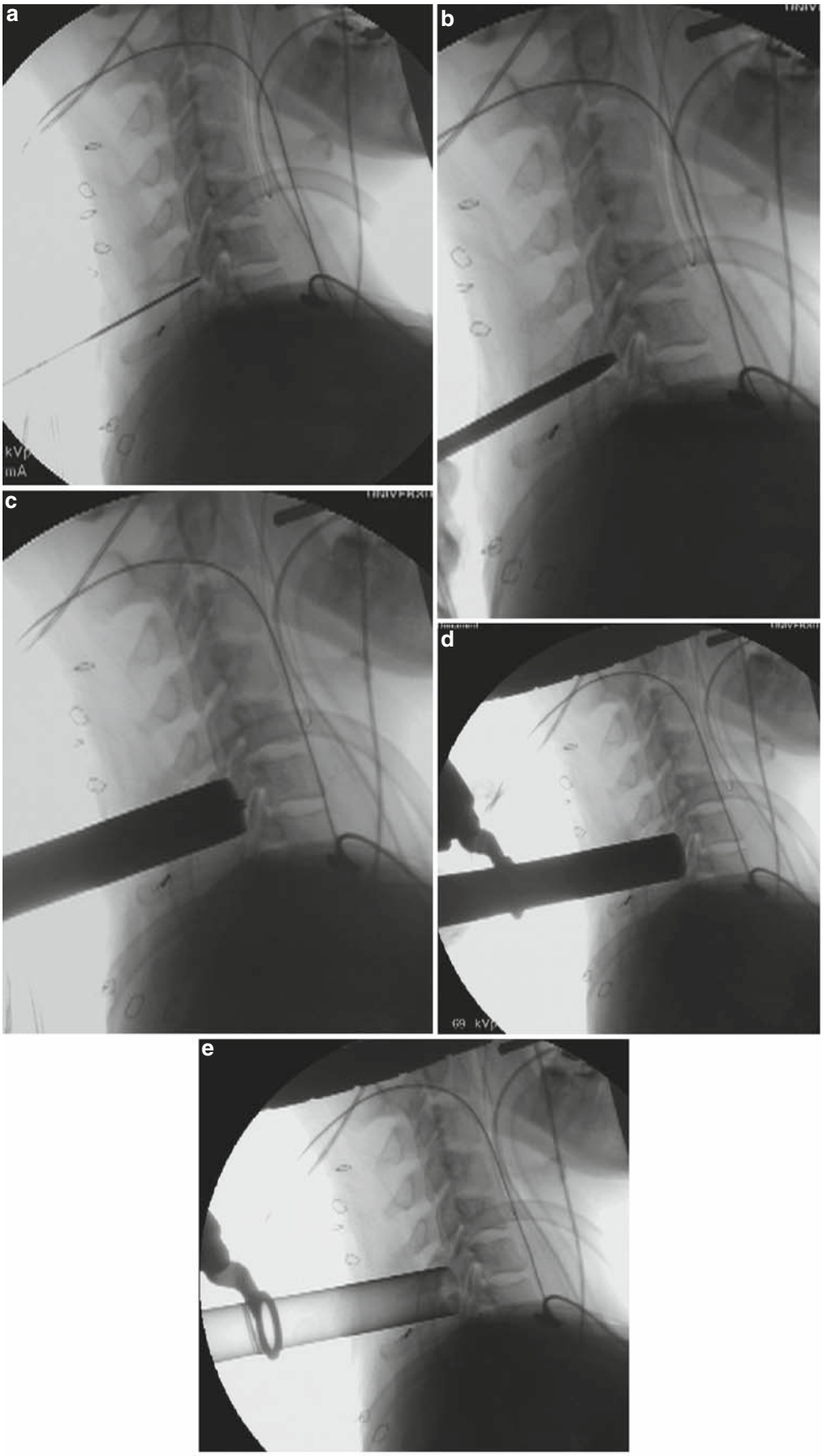

Fig. 4.3 Intraoperative lateral fluoroscopic images demonstrating process of muscle dilation. (**a**) K-wire is docked on laminofacet junction over intervertebral foramen of interest (C6-7 in this case). (**b**) The first two muscle dilators are inserted serially. (**c**) Progression to largest dilator is complete. (**d**) An 18-mm tubular retractor is placed over dilators. (**e**) Retractor is fixed into place and dilators are removed

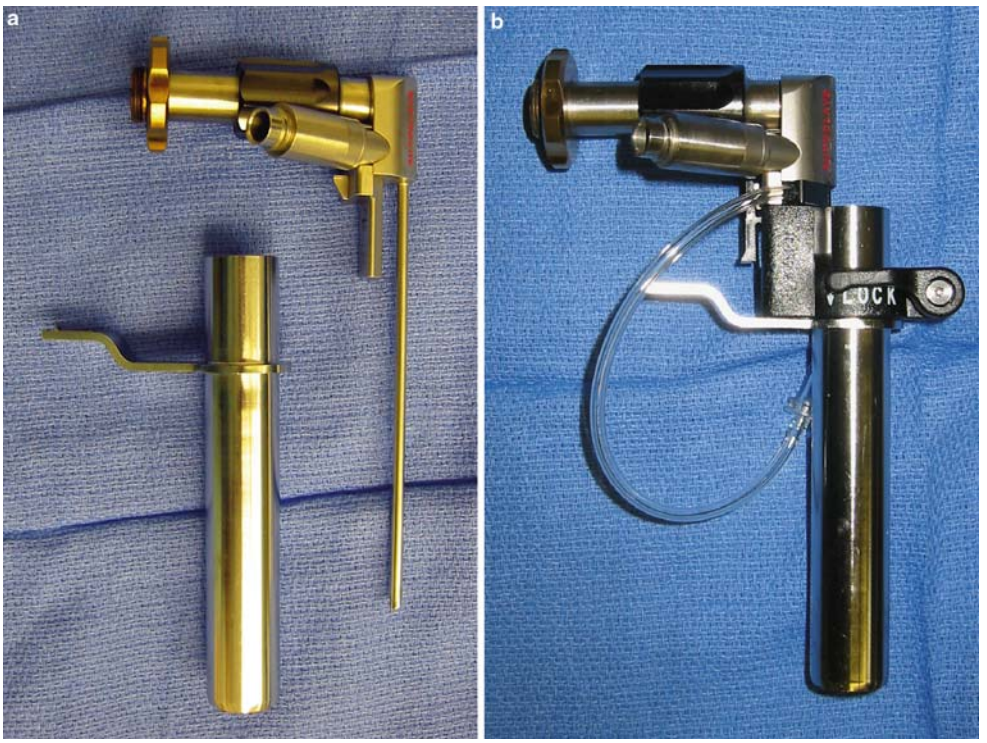

Fig. 4.4 Photographs of (**a**) METRx tubular retractor and rigid 25° glass-rod endoscope, and (**b**) endoscope inserted into tube and fixed in place with cylindrical plastic friction couple

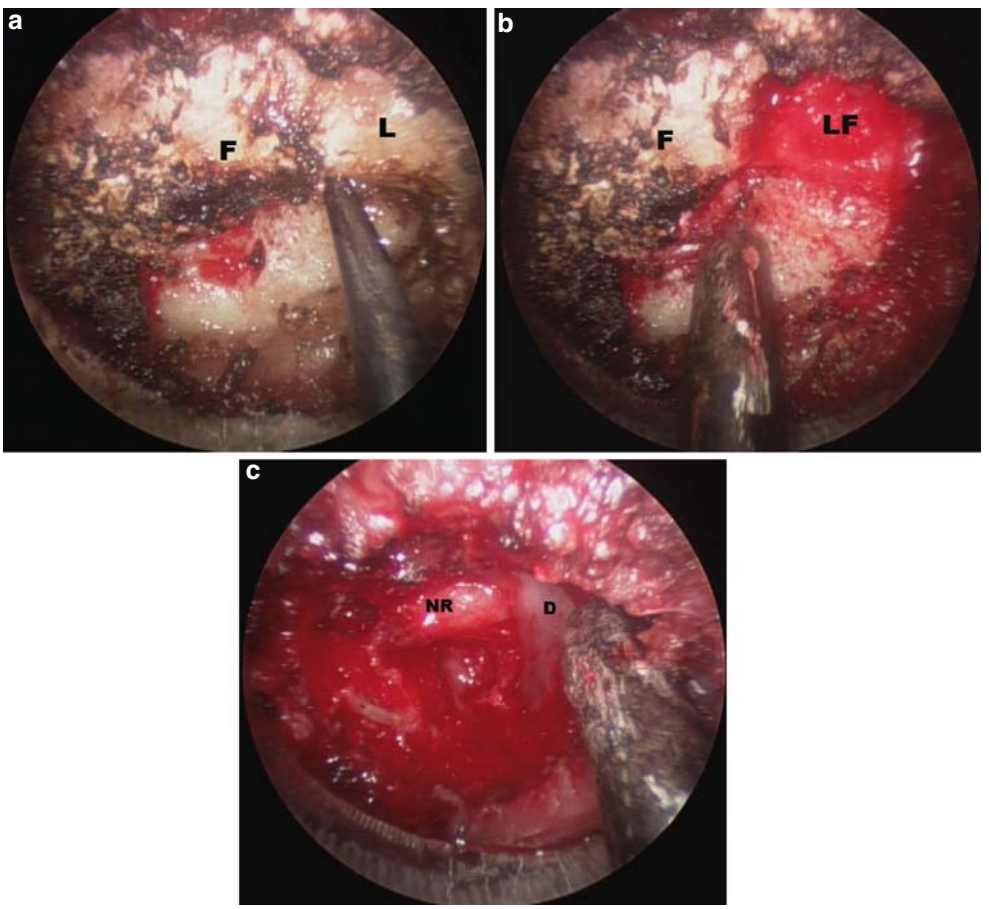

Fig. 4.5 Intraoperative endoscopic photographs during left-sided CMEF. In all photos, rostral is to the *top* and medial is to the *right*. (**a**) Initial exposure reveals lateral edge of lamina (L) joining the medial facet (F) with fine up-going curette inserted under caudal edge of laminofacet junction. (**b**) After initial laminotomy, the ligamentum flavum (LF) is seen with adjacent facet (F). (**c**) After foraminotomy, the lateral edge of dura (D) and decompressed nerve root (NR) in the proximal foramen are revealed

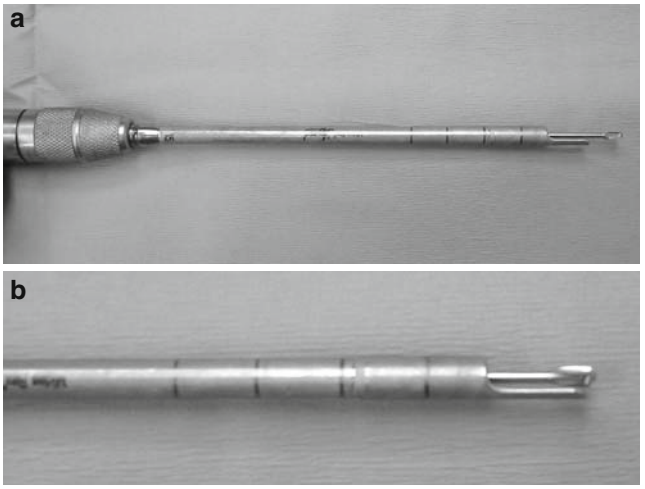

Fig. 4.6 Endoscopic drill with TDQ bit (Midas Rex, Fort Worth, TX) and guard sleeve in (**a**) retracted and (**b**) extended positions

removal. In the case of a soft disc herniation, a nerve hook may be passed ventrally and inferiorly to the root to gently tease the fragment away from the nerve for ultimate removal with a pituitary rongeur. In either case, additional drilling of the superomedial quadrant of the caudal pedicle allows greater access to the ventral pathology and obviates the need for excessive nerve root retraction superiorly. The foramen is inspected one final time for any further signs of compression, and the field is irrigated with antibiotic-impregnated solution. Hemostasis is achieved with bipolar cautery, bone wax, and any of a variety of commercially available operative hemostatic agents. A methylprednisolone-soaked pledget may be placed over the root to reduce postoperative inflammation. Closure and postoperative care proceed as described below.

CMEDS Technique

After completion of the ipsilateral laminotomy, the ligamentum flavum is left in place to protect the dura. The tube is then angled about 45° off the midline such that the endoscope and tube are oriented to visualize the contralateral side. A plane between the ligament and undersurface of the spinous process is gently dissected with a fine curette. The drill with guard sleeve extended [Fig. 4.6(b)] is then used to progressively drill the undersurface of the spinous process and contralateral lamina all the way to the contralateral facet. This initial decompression allows a greater working space within which to remove hypertrophied ligament while avoiding downward pressure on the dura and spinal cord. Dissection and removal of the ligament with curettes and Kerrison rongeurs may now proceed safely. Any compressive elements of the contralateral facet or the superior edge of the caudal lamina may also be drilled off or removed with Kerrison rongeurs at this time, as their impact on the dura is more apparent with the ligament removed. After gently confirming decompression over to the contralateral foramen with a fine probe, the tube is returned to its original position to complete the ipsilateral removal of ligament and bone. This should then reveal completely decompressed and pulsatile dura (Fig. 4.7). If indicated, ipsilateral foraminotomy as described above may be performed at this time as well. The field is irrigated with antibiotic-impregnated solution, and hemostasis is achieved with bipolar cautery, bone wax, and hemostatic agents. Figure 4.8 demonstrates a representative case of single-level C4-5 stenosis treated with CMEDS. The typical extent of bony decompression is seen on postoperative CT [Fig. 4.8(c)].

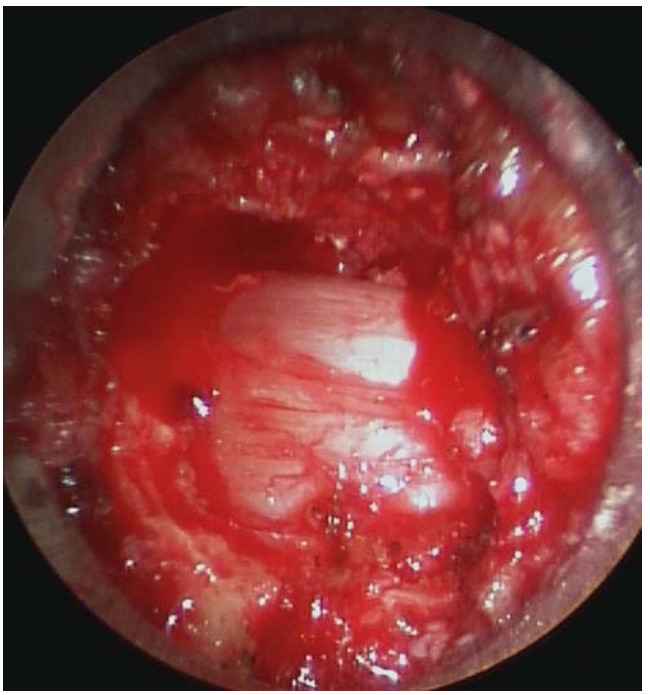

Fig. 4.7 Intraoperative endoscopic photograph during right-sided approach for CMEDS. The dura is seen to be completely decompressed in this image following removal of offending bone and ligament. Rostral is to the *right* and lateral is to the *bottom*

Closure and Postoperative Care

The tube is removed, and local anesthetic is injected into the fascia and muscles surrounding the incision. The wound is closed using one or two absorbable stitches for the fascia, two or three inverted stitches for the subcutaneous layer, and a running subcuticular stitch and

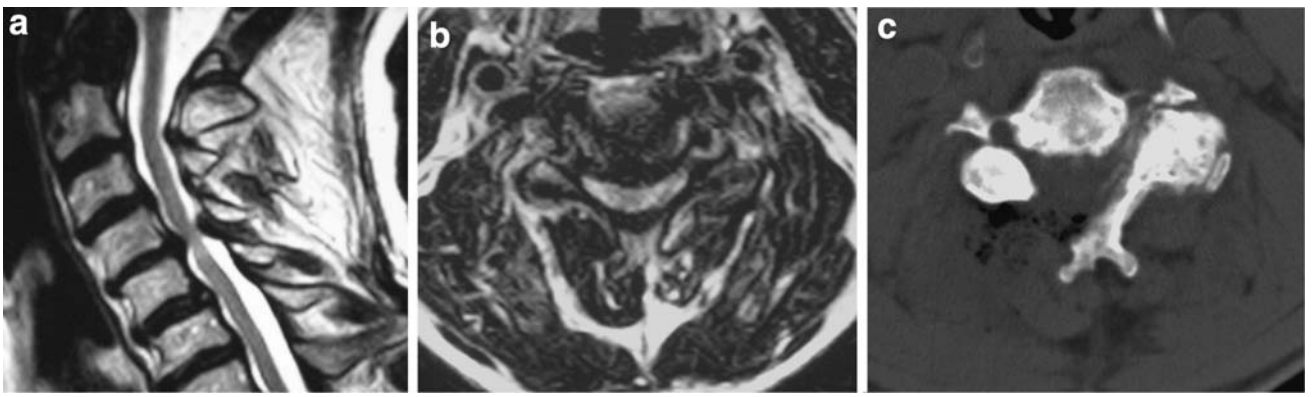

Fig. 4.8 An 80-year-old male presented with chronic myelopathy from cervical stenosis and underwent right-sided approach for C4-5 MEDS. (**a**) Sagittal T2-weighted MRI demonstrates focal C4-5 spondylotic stenosis with signal change in the spinal cord. (**b**) Axial T2-weighted MRI reveals severe focal compression at C4-5. (**c**) Postoperative axial CT image shows typical extent of bony resection required to achieve adequate decompression of the spinal cord. Note the preservation of the dorsal spinous process and contralateral lamina and facet. Also, note the minimal impact on paraspinal soft tissues on the approach side (postoperative air is seen on the approach side and at the site of the laminotomy)

Dermabond for the skin (Fig. 4.9). No dressing need be applied. The patient is returned to a supine position and the Mayfield is removed. After awaking from general anesthesia, the patient is brought to the postanesthesia care unit and mobilized as early as possible. No collar is necessary. If medically stable, patients are typically discharged home after 2–3 hours, although in some cases we have chosen to observe our CMEDS patients overnight. Discharge medications generally include an opioid/acetaminophen combination pain reliever and a muscle relaxant. Nonsteroidal antiinflammatory agents are also commonly used.

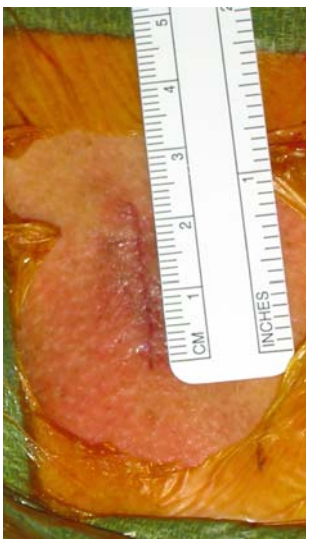

Fig. 4.9 CMEF/D or CMEDS incision after closure is only 2 cm in length

Complications

Typical complication rates from posterior cervical decompressive procedures range from 2-9% and are mostly attributable to infection and cerebrospinal fluid (CSF) leak [9]. We have not had any infections in our series to date, and our unintended durotomy rate has dropped from 8% in the initial series of patients [9] to around 1% more recently. Direct suture repair of durotomy is difficult through the narrow-diameter tubes. Therefore, one technique for handling small defects is to simply cover the durotomy with muscle, fat, gelfoam, or dural substitute followed by fibrin glue or synthetic sealant such as Coseal (Baxter Healthcare, Glendale, CA). Using this approach, overnight bedrest is usually sufficient to seal the defect. For larger dural tears that cannot be primarily closed, —two to three days of lumbar CSF drainage may prevent a leak. Ultimately, the small opening and relative lack of dead space after minimally invasive procedures have made the incidence of postoperative pseudomeningoceles and CSF-cutaneous fistulae negligible.

Potential neurological complications include radicular injury from manipulation within the tight foramen or direct mechanical spinal cord injury during dilation or decompression. Vertebral artery injury can be avoided by early detection of dark venous bleeding from the venous plexus surrounding the artery that may arise from accidental dilation lateral to the facet or during overly aggressive dissection laterally in the foramen. This type of bleeding can typically be controlled by packing with gelfoam or other hemostatic product. As mentioned previously, despite the use of the semisitting

position, air embolism has not presented a problem to date. Delayed complications such as recurrent disease or postoperative instability also have not yet been observed in our use of these techniques thus far.

Pearls and Pitfalls

- Carefully dock the K-wire on solid bone of the lateral mass to avoid plunging into the canal.
- Sharply incise the cervical fascia the length of the skin incision prior to inserting the first dilator to allow safe dilation.
- Preserve at least 50% of the facet complex for postoperative stability.
- During CMEDS, generous drilling of the undersurface of the spinous process and contralateral lamina will prevent undue downward pressure against the ligamentum flavum and, therefore, the dura and spinal cord.

Conclusion

Posterior CMEF/D and CMEDS offer the benefits of decreases in blood loss, length of stay, postoperative pain, and muscle spasm; preservation of motion segments; and decreased risk of iatrogenic sagittal plan deformity, but they still deliver efficacy equivalent to their open counterparts [9]. Ultimately, it is the reduction in immediate and delayed morbidity combined with safe and effective decompression that makes these minimally invasive approaches to cervical degenerative disease so appealing. Their use will and should continue to expand as more surgeons become familiar with microendoscopic techniques.

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Posterior Cervical Instrumentation and Fusion

5

Farbod Asgarzadie, Barón Zárate Kalfópulos, Vartan S. Tashjian, and Larry T. Khoo

Introduction

A variety of techniques have been developed for the internal fixation of the subaxial cervical spine through a posterior approach [1, 2]. These include interspinous wiring with bone graft, interlaminar clamps, hook plates, Daab plates, lateral mass metallic plates, and Harrington rod constructs.Before the advent of lateral mass screw fixation, interspinous wiring was commonly used for multilevel fixation. Using this technique, three wires were passed through holes made at the spinolaminar junction and around the rostral border of the rostral spinous process [Figs. 5.1(a), (b)] [3–5]. For cases requiring laminectomy with removal of the spinous processes, various facet-wiring techniques were developed with and without bone grafting for purposes of stabilization [Figs. 5.2(a)–(e)]. Combinations of oblique facet and spinous wiring were also developed, providing biomechanically superior fixation [Figs. 5.2(f), (g)]. The strength of this construct has been verified in biomechanical studies, and excellent union has been reported in case reviews [6–8]. Luque rectangles utilizing a triple-wiring technique through the facets were utilized in cases where the dorsal spinolaminar sites were unavailable, such as in severe posterior column injury. Unlike simple interspinous wiring, this technique allowed for the ability to bridge large dorsal column defects (e.g., after tumor resections) and provided greater rotational and torsional stability [9, 10]. In the late 1970s, Roy-Camille's group described a novel technique for posterior cervical instrumentation in which plates were secured to the lateral masses by the use of screws, a technique that proved to be significantly stronger than previous constructs on biomechanical cadaveric testing [Figs. 5.3(a)–(c)] [11–15].In cases of cervical trauma utilizing this technique, 95–100% fusion rates were reported when autogenous bone grafting was performed [16, 17]. Because lateral mass screws at C7 may oftentimes render a suboptimal purchase, pedicle fixation of the lower cervical spine and upper thoracic vertebrae has been proposed by several authors [18–24]. Transpedicular screws have been shown to have more fixation stability compared to other midcervical reconstruction systems [25].

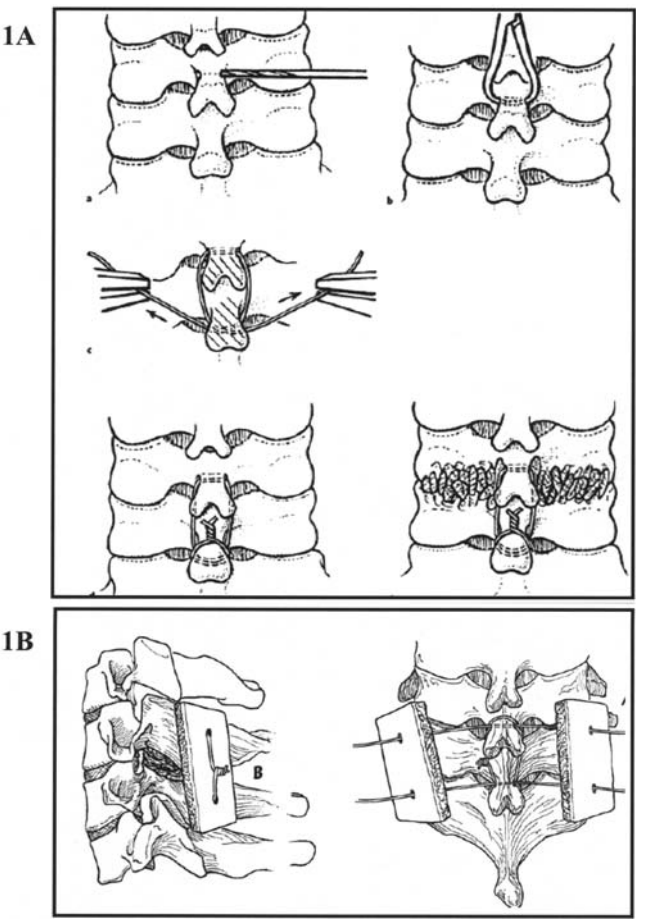

Fig 5.1 (**a**) Interspinous wiring technique; (**b**) with lateral mass bone grafting

F. Asgarzadie (✉)
Department of Neurosurgery, Loma Linda University Medical Center, Loma Linda, CA 92354, USA
e-mail: farbodasgarzadie@yahoo.com

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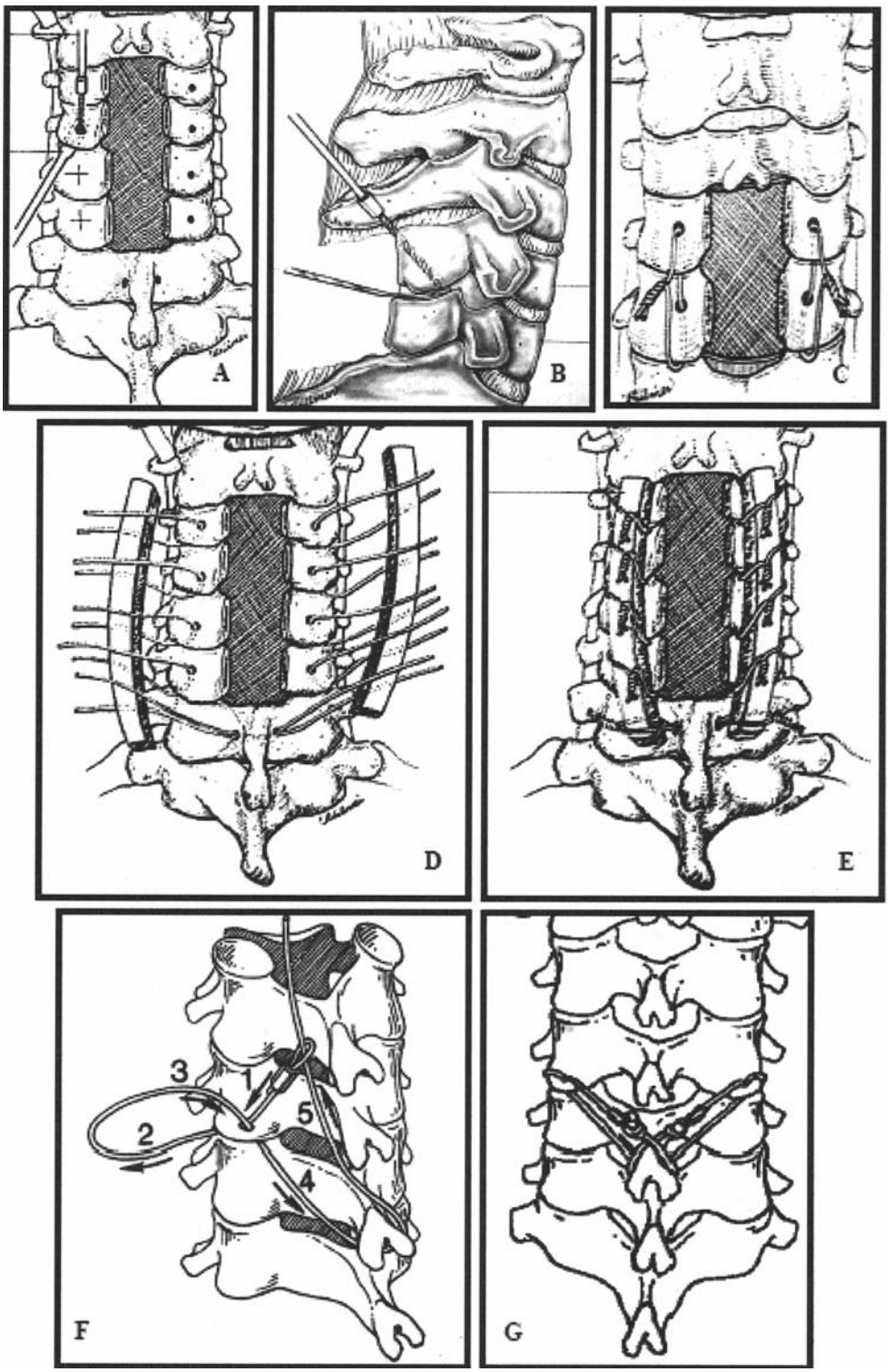


Fig 5.2 (**a–e**) Facet-wiring techniques with and without bone grafting. (**f, G**) Oblique facet and spinous processes

More recently developed instrumentation systems utilize two rods and variable screw islets at each level. These include the Axon (Synthes), Summit® (Depuy Acromed), S4 OCT (Aesculap), and Vertex® (Medtronic Sofamor-Danek) systems [Fig. 5.3(d)]. These systems vary by the angulation of their screws and in the degree of the constraint placed at the screw-rod interface. The polyaxial tulip connectors of the screws are able to angle with varying degrees of rotational freedom in each direction. These systems make segmental fixation achievable from a top-loading approach and thus allow for the possibility of minimally invasive posterior cervical fixation.

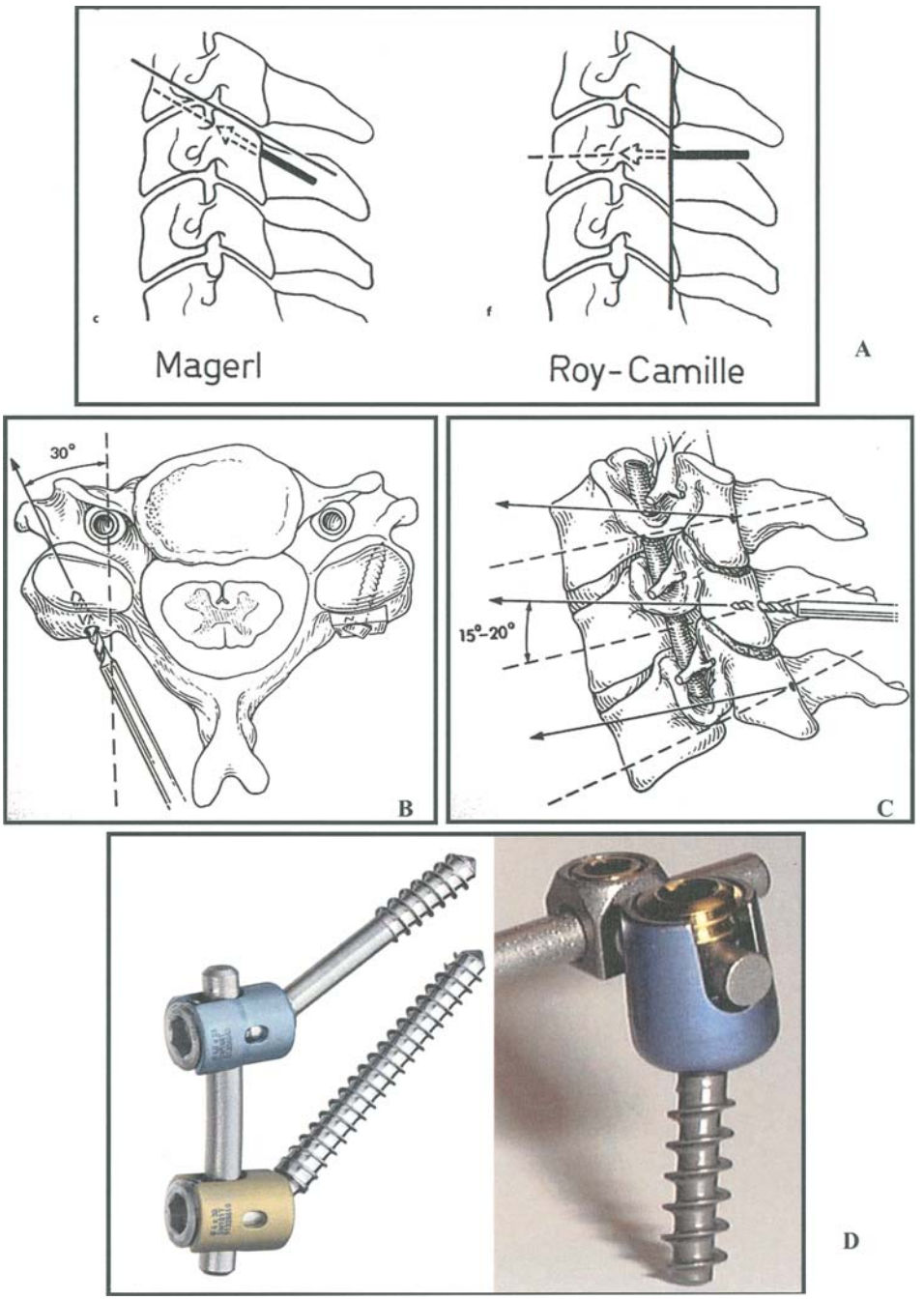


Fig 5.3 (**a–c**) Lateral mass screw fixation techniques. (**d**) Typical lateral mass screw and rod constructs

Rationale and Indications for a Minimally Invasive Approach

Decompression and fixation of the posterior cervical spine have been well established for a variety of indications, including degenerative disease, trauma, tumor, infection, and deformity. With the advent of minimally invasive surgical techniques of the spine over the past decade, there have been significant improvements in the approach-related morbidities encountered with traditional techniques. The subperiosteal muscle dissection required in standard open procedures devitalizes the affected tissue and detaches crucial muscular and ligamentous insertions that can therefore disrupt the posterior musculoligamentous dynamic tension band. Traditional exposures can also cause substantial blood loss, muscular atrophy, and potentially large cosmetic defects. As a consequence of such iatrogenic injury, the effectiveness of some traditional open procedures has been limited due to the potentially high level of postoperative disability.

As described in the previous chapter, one such example is the evolution of the decompressive posterior cervical

laminoforaminotomy for lateral recess and neural foraminal decompression. The procedure has been shown to achieve symptomatic relief in 93–97% of patients who suffer from isolated cervical radiculopathy due to compression by disc or osteophyte [Fig. 5.4(a)] [26–29]. Enthusiasm for this surgery, however, was tempered by the considerable cervical muscular pain and spasm that often followed, resulting in slower recovery, especially in cases where the use of a wider incision was necessary for adequate visualization. A minimally invasive microendoscopic foraminotomy minimizes the amount of tissue trauma and muscle injury, thereby overcoming the

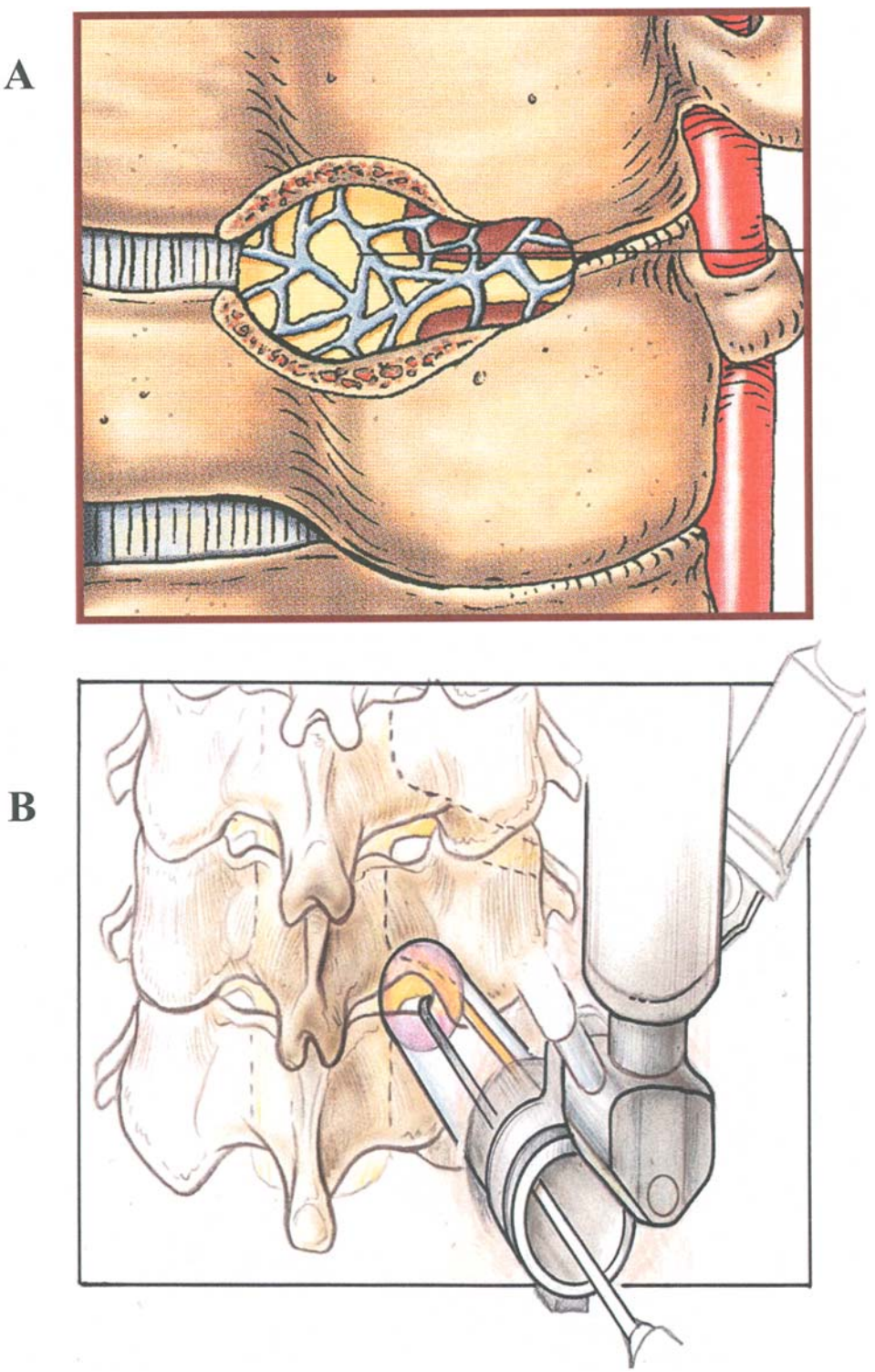


Fig 5.4 (**a**) A traditional open decompressive posterior cervical laminoforaminotomy for lateral recess and neural foraminal stenosis. (**b**) A minimally invasive microendoscopic foraminotomy

problems of postoperative pain and muscle spasm with the same clinical results as that of the classical open cervical foraminotomies [Fig. 5.4(b)] [30, 31].

Through the same minimally invasive path of tubular access, the lateral masses of the cervical spine can be readily approached.A 20- or 22-mm portal can expose two adjacent lateral masses, and with the advent of some of the newer types of expandable access portals, up to three lateral masses can be instrumented through a single exposure.The portals allow for the placement of top-loading polyaxial screws for posterior cervical lateral mass fixation. Minimally invasive posterior cervical fixation (MI-PCF) has been applied with excellent clinical and radiographic results in cases requiring lateral mass fixation [32, 33]. The widespread popularity of simple top-loading polyaxial screw systems has also greatly facilitated the MI-PCF procedure.

Positioning and Setup

For the MI-PCF procedure, local anesthesia and intravenous sedation are inadequate due to the substantial risk of neurovascular injury in case of any accidental movement by the patient. Therefore, general endotracheal anesthesia is preferred along with rigid head fixation using a three-point head holder. Depending on the exact nature of the pathology, consideration should be given to fiber-optic intubation. Patients may be positioned either prone or sitting. An intermediate semisitting position may be helpful due to the reduced epidural venous engorgement and consequent decreased intraoperative blood loss with a minimal risk of air-embolic events. As our experience with this surgical technique has grown, we no longer routinely place a CVP catheter due to the minimal blood loss of the operation.Prior to finalizing the head positioning, utmost care should be directed to ensuring that the cervical spine and neck musculature are not twisted or held in a grossly unusual position. Furthermore, the neck, chin, and chest must be allowed to remain loose and free of compression, and all routine pressure points should be adequately protected.

Intraoperative somatosensory evoked potential (SSEP) monitoring of the operated dermatome and distal distributions is highly recommended in order to monitor the spinal cord integrity during surgeries where decompression is to be combined with fixation. Electromyographic recordings can also be used to assess the motor integrity of the involved nerve root and to stimulate the screws to increase the safety and accuracy. This requires that the anesthesiologist refrain from the use of neuromuscular paralytics following induction in order to allow for improved feedback from the nerve root during the operation. For most cases, a single intraoperative dose of either Cephazolin or Vancomycin is used for prophylaxis against infection. We do not typically use corticosteroids for these procedures.

Intraoperative real-time imaging is a necessity for MI-PCF; therefore, a fluoroscopic C-arm should be brought into the surgical field. While lateral imaging is most commonly used for this procedure, the C-arm should be positioned in a manner that allows for easy rotation into various positions since visualization in other planes may become necessary; for example, anteroposterior fluoroscopic images can be helpful during the initial localization. Whereas lateral mass fixation can be accurately performed using anatomic landmarks, cervical pedicles should be cannulated with the use of supplemental lateral or anteroposterior (AP) fluoroscopic confirmation whenever feasible.

Tubular Dilation and Exposure

The ultimate trajectory of the working portal matches that of the lateral mass screws. This trajectory dictates the proper placement of the skin incision.As such, lateral fluoroscopy is essential for safe and appropriate guidance and to ensure the proper ergonomic placement of the working portal directly on target.

After the patient is properly positioned, a Kirschner wire (K-wire) is placed lateral to the neck to exactly parallel the facet of interest to determine the center of the skin incision. The skin entry point lies two to three segments below the target level in the sagittal plane at the midline and typically approximates the trajectory used during open lateral mass fixation. Confirmation of the appropriate trajectory is also done in the AP plane as well [Fig. 5.5(a)]. Once this entry point has been determined, under fluoroscopic guidance, the K-wire is inserted through the posterior cervical musculature and fascia to the target facet. One must take care to approximate the desired screw orientation by remaining parallel to the facet joint in the sagittal plane, with the pin trajectory directed in a superior and lateral direction. Particular caution should be taken at this point to ensure that the guidewire is docked on bone to avoid inadvertent damage to the spinal cord by being too medial. To decrease the chances of this type of an interlaminar breach, it is recommended to aim more laterally during this docking maneuver. The K-wire should ideally rest in the medial aspect of the facet complex; this can be confirmed through AP fluoroscopy [Fig. 5.5(b)].

Once the guidewire is docked on the facet in question, the skin incision should be extended above and below the

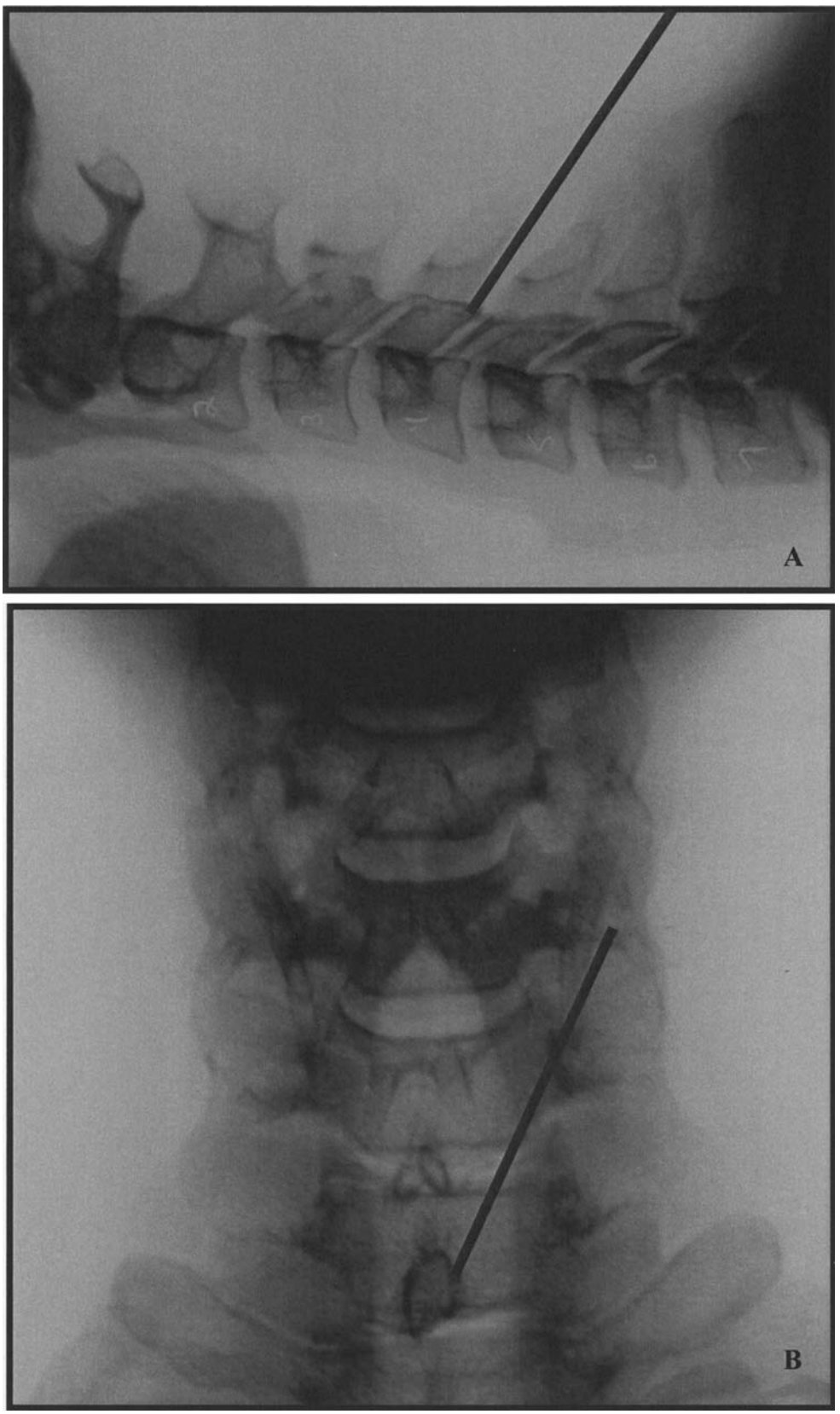


Fig 5.5 (**a, b**) Confirmation of the appropriate trajectory for a minimally invasive cervical foraminotomy in the AP and lateral planes

K-wire entry point for about 1 cm in each direction and deepened sharply to just below the level of the fascia, taking care not to cut muscle fibers during this procedure, to avoid unnecessary bleeding. Sharp opening of the fascia allows for easier and safer passage of the sequential dilating cannula. Any plastic adhesive skin barriers should be circumferentially removed from the edges of the incision to prevent inadvertent sequestration of material into the wound.

Sequential dilators are then inserted through the soft tissues and docked on the facet of interest. Real-time lateral fluoroscopic images should be obtained as often as needed to ensure a proper working trajectory throughout this process of serial cannula dilation. A final tubular working channel is inserted and docked at the junction of the lamina and the lateral mass [Figs. 5.6(a)–(c)]. A variety of these working channels are available,including fixed 20- or 22-mm portals provided by the METRx ® tubular access system (Medtronic Sofamor-Danek) and the Harmony system (Spinal Concepts) [Fig. 5.6(c)]. As an alternative, expandable cannulas such as the Quadrant® system (Medtronic Sofamor-Danek) can provide a greater working space and more flexible approach angles for hardware placement, especially when two or more

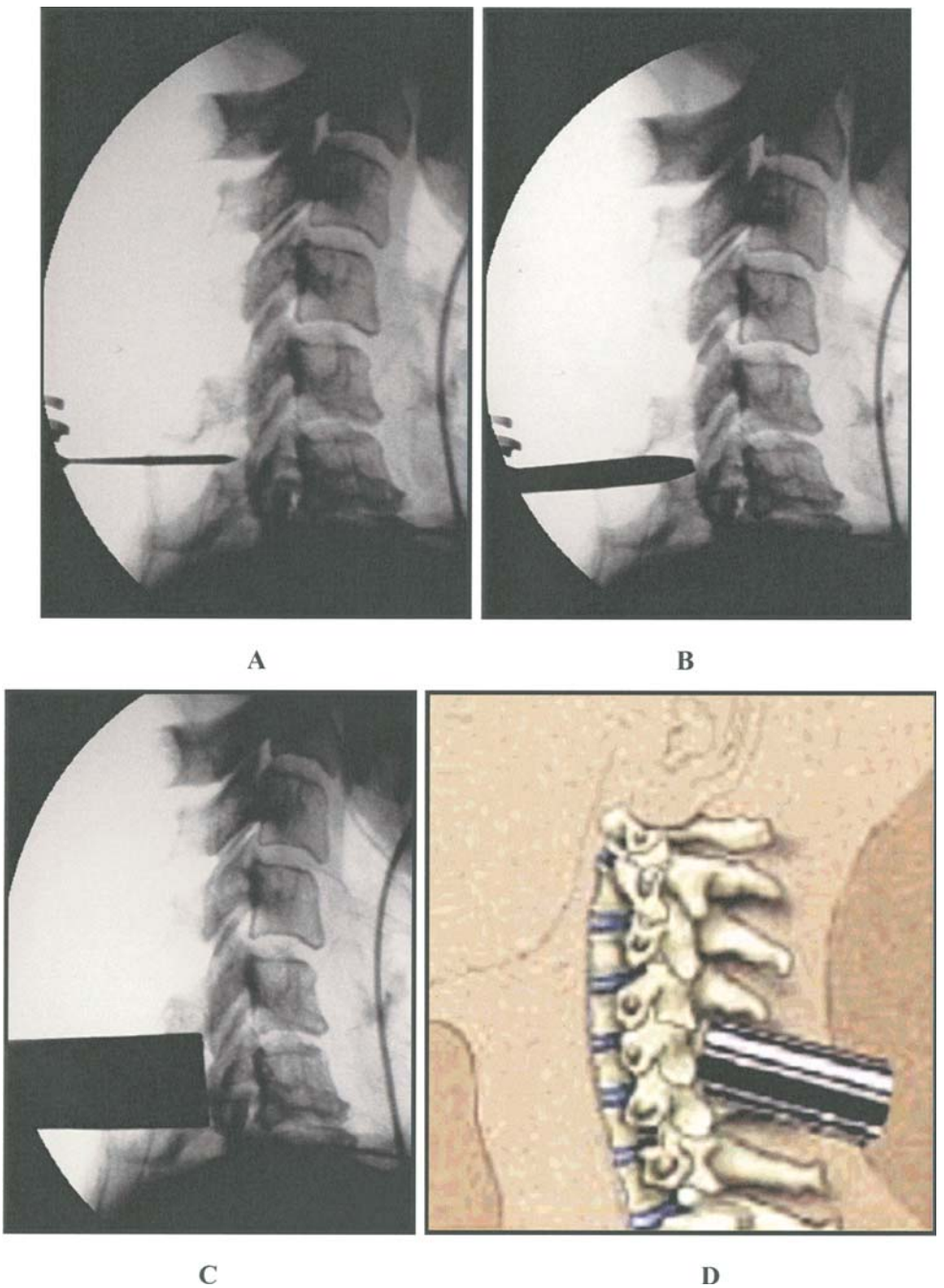


Fig 5.6 (**a–c**) Lateral fluoroscopic images showing sequential dilation for a C5-6 minimally invasive foraminotomy

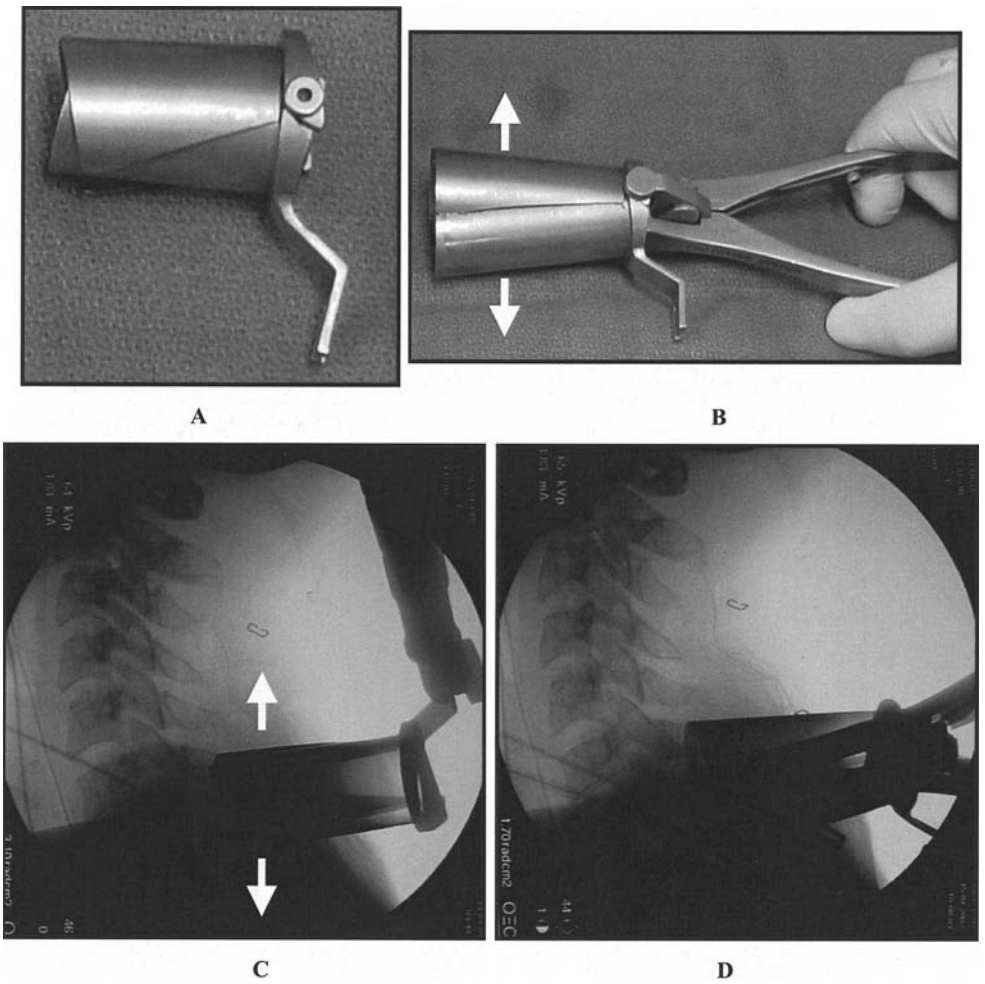
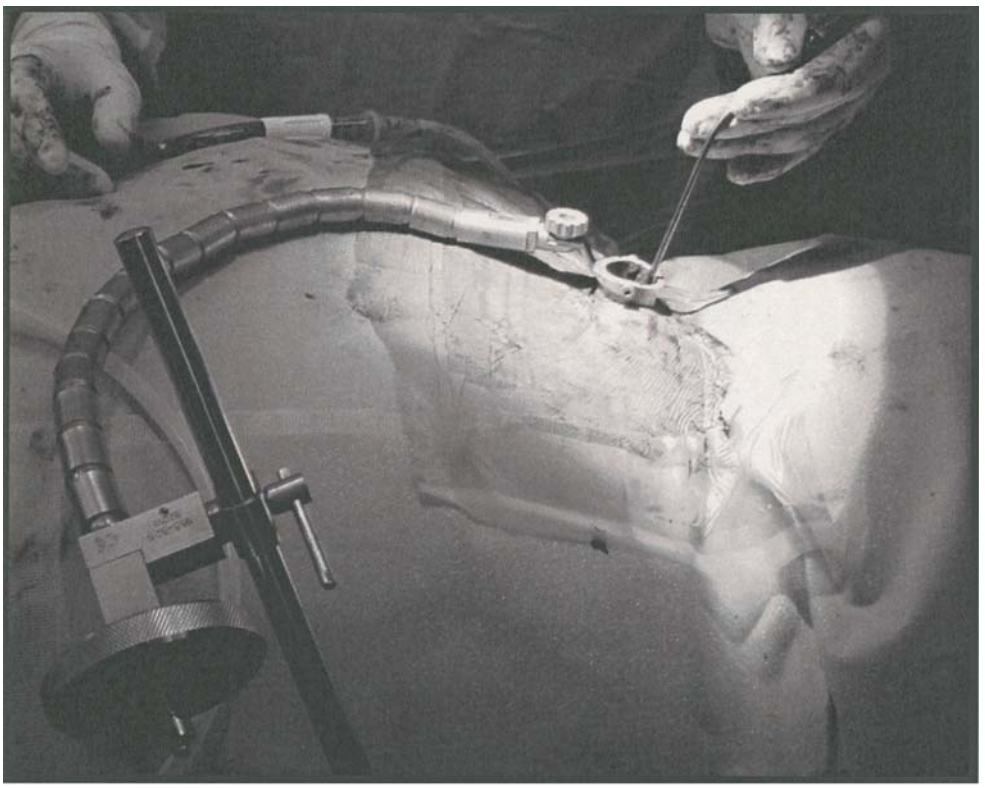


Fig 5.7 (**a–d**) Expandable cannulas can provide a greater working space and more flexible approach angles for hardware placement, especially when two or more levels need to be addressed. The cannula shown here is the Quadrant® system (Medtronic Sofamor-Danek)

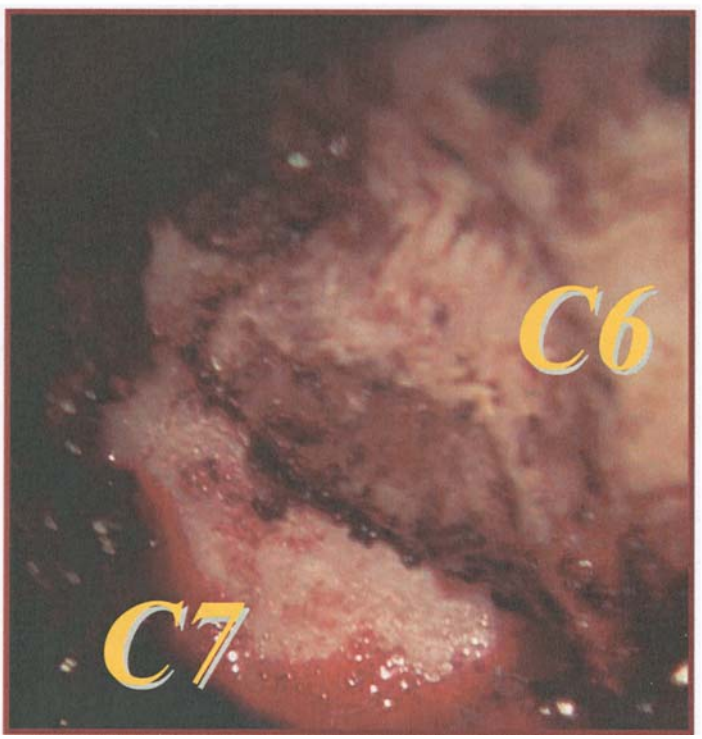
levels need to be addressed [Figs. 5.7(a)–(d)]. Once the position of the working channel has been confirmed using fluoroscopy, it is attached to a flexible retractor affixed to the side rail of the table and then locked into position (Fig. 5.8). Visualization can be achieved using loupe magnification, an operating microscope, or an endoscope. If employed, the endoscope should be white-balanced and an antifog agent should be applied to the lens, after which the endoscope is attached to the tubular retractor via a mounting stage.

Instrumentation

The minimally invasive technique for screw placement does not significantly differ from the open methods once the lateral mass has been exposed. For cases of trauma and/or cervical stenosis, decompression of the exiting root via the previously discussed minimally invasive cervical foraminotomy techniques can be executed prior to placing the screws. Similarly, cases of jumped facets can be drilled and reduced prior to placing the posterior instrumentation as well. The exiting nerve root is more likely to be encountered by a screw trajectory that is aimed too low, and the vertebral artery is more likely to be damaged by screw trajectories that are excessively medial. Thus, in order to avoid the neurovascular structures, the technique focuses on placing the screw into the upper lateral quadrant of each lateral mass. There are various methods for screw placement into the cervical lateral masses. The first report of the procedure described screw placement directed forward and outward 10° [13]. Subsequent modifications recommended placing the screw at a point slightly medial to the center of the facet and directing it 25° laterally and about 40° cephalad [34]. Other authors advocated for a technique in which the entrance point of the screw is 1 mm medial to the center of the lateral mass and aimed 15–20° cephalad and 30° laterally [35].The outer cortex should be pierced with



A



B

Fig 5.8 Flexible retractor arm connecting the working portal to the side rail of the table and then locked into position

either an awl or a high-speed drill in order to prevent the drill from sliding over the lateral mass instead of entering the bone during screw placement. For C3–C6 (and sometimes C7), it is recommended that the drill holes be made with a 15–20° cephalad angle and a 30° lateral trajectory. This rostral angle targets the transverse process and decreases the chance of damage to uninvolved joints. By starting the drill hole 1 mm medial to the center of the

lateral mass and aiming laterally, there is less risk of damage to the vertebral artery, which usually lies anterior to the junction of the lamina and the lateral mass.After drilling, the dorsal cortex can be tapped using the 3.5-mm cancellous tap. Because the majority of the new polyaxial screws are self-tapping, this step is not essential.

The screw length should allow for full penetration of the outer cortex and cancellous bone, and, in case of trauma, bicortical screw penetration may help to achieve a better purchase. The lengths typically vary between 12 and 16 mm but are affected by factors such as the patient's specific anatomy, the presence of dorsal osteophytes, and the exact screw trajectory. Although violations of soft tissues by an overly lengthy screw are seldom problematic if the trajectory is correct, preoperative measurements from CT scans can be helpful in determining the best screw length, especially if a bicortical screw purchase is desired.

Care must be taken to fully expose the facet joints and lateral borders of the lateral masses, which can be readily accomplished with a shielded monopolar cautery combined with pituitary rongeurs. While the capsular ligaments and soft tissue around the facets are removed, the facet joints above and below the involved ligaments should remain intact to prevent late instability or fusion at those levels. The monopolar cautery can be used to stop bleeding such as that from the venous plexus lateral to the lateral masses; however, caution should be exercised to avoid inadvertent injury to the vertebral artery by avoiding overly aggressive cautery in this region.Alternatively, gentle tamponade with Gelfoam® or Surgifoam® will often effectively stop the bleeding from this venous plexus.

For cases where facet realignment is not necessary, the lateral mass screws can simply be placed in an in situ fashion. If an open reduction is needed, a high-speed drill can be used to remove a portion of the superior articular process of the inferior vertebrae, and a Penfield-type instrument can then be inserted within the facet and rotated to elevate and posteriorly displace the subluxed lateral mass into proper anatomical alignment. An alternative method for open reduction involves disengaging the head holder after drilling of the facet edges, followed by gentle inline traction, appropriate anterior translation, and counterrotation opposite to the mechanism of injury for proper facet realignment. The head holder is then relocked and the facet complex fused in situ.It is highly recommended that SSEP monitoring combined with nerve root surveillance at the pathologic level be used during such maneuvers. Should neural decompression be necessary, it is recommended that the screw sites be marked, drilled, and tapped prior to removing the laminae. This method protects the dura and spinal cord during the drilling process [32].

The joint cartilage from the facets should be removed prior to instrumentation, and the joint should be decorticated using a high-speed drill with a small bit. Although there is a wide body of literature demonstrating successful arthrodesis without the use of bone graft, it is generally recommended to use bone grafts, such as cancellous autologous bone from the iliac crest, within the facets as well as over the decorticated laminofacet junctions. Given the postoperative pain syndrome associated with iliac bone harvesting, as an alternative source of autologous bone, the dust obtained during facet drilling, laminotomy, and foraminal decompression can be used. This graft can then be combined in a one-to-one ratio with an appropriate bone extender, such as demineralized bone matrix or calcium triphosphate substitutes.

After denuding the facet and placing the bone graft, the surgeon inserts an appropriately sized lateral mass screw under both direct visualization and fluoroscopic guidance. Depending on the size of the lateral mass, 14- or 16-mm-length, 3.5-mm-diameter, screws are typically used.The exact size can be measured on the CT scan or estimated from lateral intraoperative fluoroscopy [Figs. 5.9(a), (b)]. The tubular retractor arm usually must be relaxed at this point to allow easy acquisition of the second screw trajectory, following which the second screw is placed in the manner detailed above.

Since the C7 lateral mass is much thinner than that of the more rostral levels, the placement of a lateral mass screw may prove to be excessively difficult; therefore, a pedicle screw may need to be used at this level instead. Furthermore, cervical pedicle screws may attain greater pullout strength than lateral mass screws due to the greater length and circumferential cortical penetration. Cervical pedicle screws may also be used in levels where the lateral mass is fractured or unusable. There is usually no vertebral artery in the transverse foramen, allowing for safe pedicle screw placement at this level and at T1. For C7 pedicle screw placement, the drill is generally angled 25–30° medially and perpendicular to the rostral-caudal plane.At the T1 level, the angle is usually 10–15° medially and 5° caudally.A careful examination of the preoperative CT scan is important in order to determine the pedicle size and to gauge the appropriate angle. Usually, a 4.0-mm cortical screw of 20- to 22-mm length is sufficient in size. A small laminotomy can be made to palpate the medial aspect of the pedicle, or AP fluoroscopy can be used for safer placement of the screw.

Following placement of the screws, an appropriate-sized rod is inserted into the top of the polyaxial screws and locked into place. The rod diameter generally varies from 3.2 to 3.5 mm, depending on the specific system used.Rod placement is more technically challenging when fusing three adjacent segments, but careful dorsal

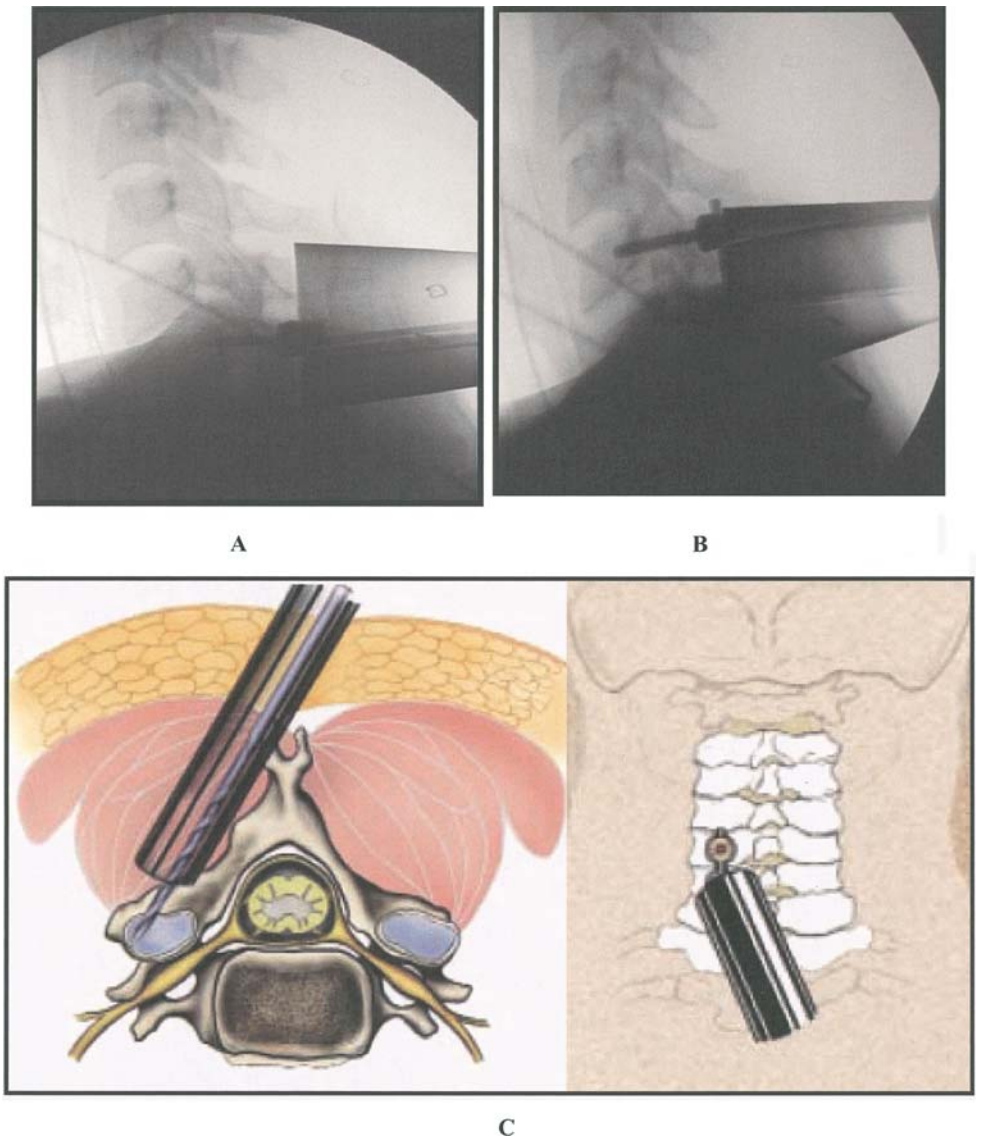


Fig 5.9 (**a, b**) Lateral fluoroscopic images showing the placement of lateral mass screws and rods through an expandable tube at C5 and C6

elevation of the tubular retractor system away from the facet joints usually creates adequate space for rod manipulation and placement. For this reason, the expandable retractors in conjunction with modern top-loading polyaxial tulip head fixation systems, such as CerviFix® or StarLock® (Synthes), Summit® (Depuy Acromed), and Vertex® (Medtronic Sofamor-Danek), are particularly useful at providing a larger working space. Once the rods have been locked into place, the construct is complete [Fig. 5.10(a)]. Appropriate lateral and anteroposterior fluoroscopy should be used at this point to confirm proper bony alignment and construct placement, following which the tubular retractor is removed. For cases where bilateral fixation is needed, the above steps can be repeated through the same midline incision, using a contralateral trajectory. Closure is then completed with a simple fascial 0-Vicryl® stitch followed by some degree of subcutaneous closure with 3-0 Vicryl. Skin closure can be accomplished with steri strips or a DermaBond-type closure [Fig. 5.10(b)].

Transfacet Screws

Posterior cervical fixation can also be achieved through transfacet screws. For this procedure, the optimum entry point for the screw is on the center of the lateral mass with a trajectory that is perpendicular to the facet joint. As such, the incision should be placed more rostrally in order to allow for the insertion of the K-wire in such a manner that it docks at 90° to the facet and parallel to the spinous

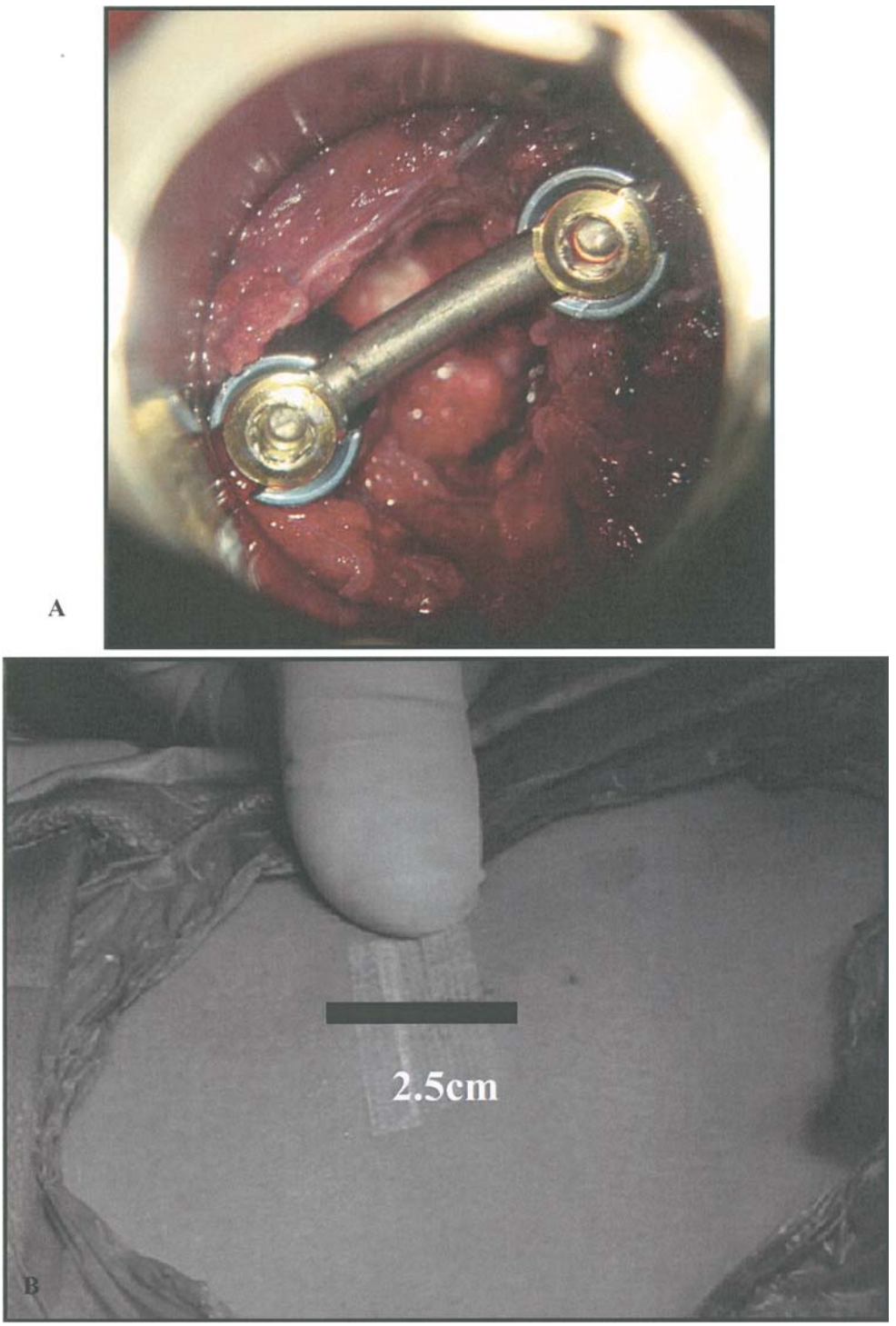


Fig 5.10 (**a**) Intraoperative picture showing a top-loading, one-level lateral mass screw and rod construct through a tubular approach. (**b**) Typical skin closure of a minimally invasive posterior cervical incision

process.Once the entry point and trajectory have been confirmed, the K-wire is driven into the superior articular process to a depth that is determined by the length of the specific compression device to be used. Fluoroscopy should be used in order to ensure the appropriate depth and trajectory.

At this point, the bone is drilled through the superior lateral mass, across the facet, and into the inferior lateral mass to a depth of about one half to two thirds of the inferior lateral mass width as guided by lateral fluoroscopy. This procedure is facilitated by systems that supply cannulated drills with depth-limiting contacts that are

designed to be passed over the K-wire, such as the 3.8-mm CS Facet Compression Device® (Triage Medical). For this system, after the proper depth has been achieved, the drill hole is tapped and the compression device is passed over the K-wire, engaged, and locked in place. The K-wire is then removed and the procedure is repeated for the contralateral side in a similar manner [Figs. 5.11(a), (b)]. For cases of simple adjunctive dorsal fixation after multilevel anterior fixation, the percutaneous inline nature of this fixation technique has proven to be extremely rapid, efficient, and cost-conscious [Fig. 5.11(c)].

While this transarticular fixation system allows for fixation at all cervical levels, including C1 and C2, a modified version of the above-mentioned procedure can also be used for arthrodesis in cases of trauma such as operative cases of Hangman's-type fractures.The initial approach for this type of surgery is similar to the transarticular procedure described above in that the entry point for the drill is at the center of the C2 lateral mass with a trajectory that is parallel to the spinous process in the lateral plain. However, instead of the device being aimed inferiorly, the trajectory in the cephalad-cauded direction is toward the superoanterior border of the C2 pedicle at a depth that allows for a bicortical purchase. Once this trajectory has been confirmed by lateral fluoroscopy, the remainder of the operation is completed as described above.

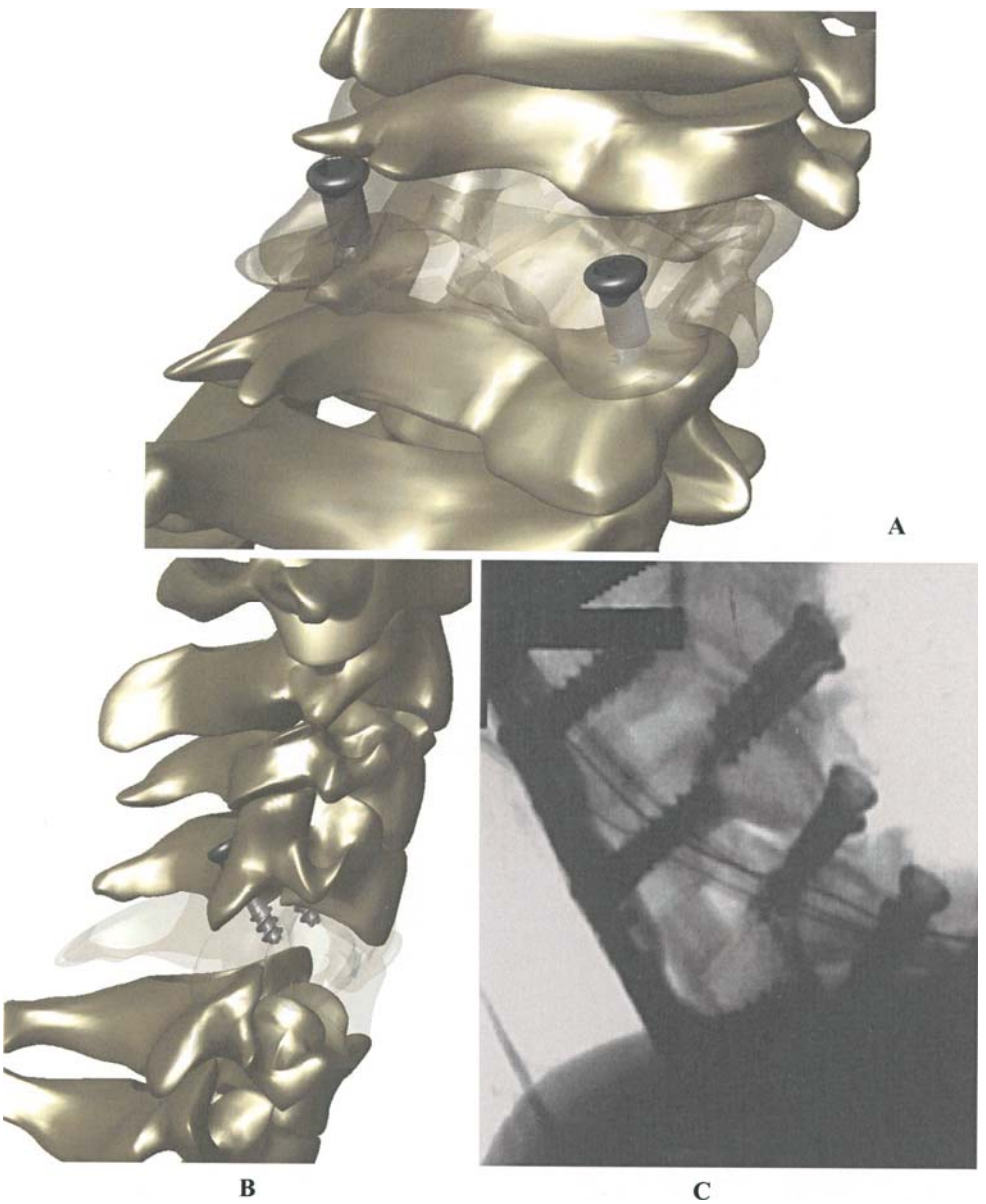


Fig 5.11 (**a, b**) The K-wire is removed and the procedure is repeated for the contralateral side in a similar manner. (**c**) For cases of simple adjunctive dorsal fixation after multilevel anterior fixation, the percutaneous inline nature of this fixation technique has proven to be extremely rapid, efficient, and cost-conscious

Closure

Prior to closure, meticulous hemostasis should be obtained by a combination of bipolar cautery and gentle tamponade with thrombin-soaked Gelfoam® or Surgifoam®. The entire wound is then copiously irrigated with lactated ringers impregnated with bacitracin antibiotics. Although optional, a small pledget of Gelfoam® soaked with methylprednisolone can be placed over the decompression defects, if present, in order to decrease local inflammation. The use of epidural morphine paste or similar cocktails is reasonable if there is no evidence of dural erosion or tear. Such agents may help to reduce postoperative pain and allow for more rapid recovery and ambulation.

The portal is cautiously removed and the soft tissue corridor is washed with antibiotic irrigation prior to a routine closure of the fascia with one or two 0-Vicryl® or similar absorbable sutures [Fig. 5.10(b)]. Because the defect is typically small, only a limited amount of closure needs to be performed, and a drain is not needed. Bupivacaine (0.25%) may be injected into the skin edges and superficial musculature prior to closure in order to minimize immediate postoperative pain. Inverted 2-0-Vicryl® stitches are usually used to close the subcutaneous layer with a 4-0-Monocryl® subcuticular closure to meticulously reapproximate the skin edges. Either Steri-Strips® or Dermabond® can then be used to cover the skin. The latter is an attractive option since it keeps the skin edges closely approximated for a 7- to 10-day period, and it provides a waterproof barrier, allowing the patient to shower almost immediately after surgery, if desired.

Pearls and Pitfalls

Although the lateral screw fixation method carries a risk of potential neurovascular injury, the proper use of the technique is associated with an extremely low incidence of complications—only 4–6%. A disadvantage of lateral mass instrumentation, however, is that it is primarily an in situ fixator and cannot be reliably used for the reduction of a significant kyphosis, which is why for major anterior compression, kyphosis, or cases with very poor bone quality in the lateral masses, an anterior approach is recommended with posterior supplemental fixation as deemed necessary to enhance the stability and maintain the operative correction.

When a CSF leak occurs in the course of an MI-PCF, direct repair is often difficult because the durotomy is usually small and access is limited. Thus, fibrin coagulation products, fat, or muscle grafts should be used. Lumbar drainage can also be used in these cases for two to three days postoperatively, combined with elevation of the head of the bed, in order to help closure of the small dural tear. Spinal headaches and nausea associated with lumbar drainage can be treated symptomatically with nonsteroidal antiinflammatory medications and bed rest. For large dural tears, direct repair can be attempted if specialized instruments are available for use through the endoscopic tube: Fine-tipped needle holders and long forceps are particularly useful in this regard.In rare instances, conversion to an open procedure may be necessary to close very large dural violations.

Clinical Experience

The initial experience with minimally invasive cervical fixation at UCLA consisted of 10 patients followed to radiographic fusion; six patients underwent a single-level fusion and four patients had two-level fusions.Instrumentation was performed at the C3–C7 segments with bilateral screw placement, with the exception of three cases where lateral mass screws were placed unilaterally due to bony fractures on the contralateral side. Seven cases were posterior supplementations of anterior fusions, and three were standalone posterior constructs. Seven of the 10 patients underwent surgery due to traumatic pathology with cervical burst fractures and fracture dislocations treated with combined anterior and posterior fusions.In three cases with bilaterally jumped facets, the treatment consisted of drilling and removing the superior facet followed by intraoperative reduction and hardware placement with fusion. Three cases were posterior supplements to an anterior vertebrectomy for neoplasia.

All procedures were accomplished successfully with the use of 18- to– 22-mm tubular dilator retractors. There were no complications or new neurologic deficits, and proper hardware placement was confirmed with a postoperative CT scan.In one case, the C6 screw was positioned fairly laterally with penetration of the lateral cortex of the lateral mass; however, no additional procedure or follow-up studies were deemed necessary, as this was still thought to provide a stable construct. Fusion was confirmed in all cases with dynamic X-rays and CT scans.

Current tubular dilator dimensions limit the feasibility of this minimally invasive approach to one- or two-level fusions, since longer-segment constructs pose a problem with rod placement. However, the development of elliptical expandable tubular dilators may allow longer constructs to be placed safely. Furthermore, strategies similar to the arc rod systems and polymerizing connecting rods, which currently allow true percutaneous transpedicular

instrumentation in the lumbar spine, may also prove to be beneficial in the cervical spine, where it may ultimately allow for the placement of longer-segment cervical constructs in a minimally invasive fashion.

Radiographic guidance is essential for safe screw placement, and fluoroscopic images may be inadequate for the lower cervical spine in patients with a short neck, large body habitus, or muscular shoulders. Image-guided systems surmount this problem and allow for virtual representation of the spine without the need for real-time X-rays. However, these systems are limited in accuracy with regard to the differences in the intersegmental relationships between vertebrae in preoperative image acquisition and final operative positioning.These inaccuracies are especially exaggerated in cases with abnormal intersegmental motion or in patients who require reduction of a fracture.

The emergence of three-dimensional fluoroscopic imaging allows for the intraoperative acquisition of axial CT renderings of the spinal column. These images are less hampered by superimposed soft tissues, which allow access to the lower cervical spine for the purpose of minimally invasive screw placement. Furthermore, because the images are acquired intraoperatively, the screw trajectories can be more reliably confirmed by guidewire placement prior to final instrumentation. Amalgams of three-dimensional intraoperative imaging modalities with frameless navigation systems will ultimately make the percutaneous placement of cervical instrumentation safe and accessible.

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Thoracoscopic Discectomy

6

Rohit B. Verma, Pablo Pazmino, and John J. Regan

Introduction

Technological advances have changed the way the spine surgeon approaches pathology within the thoracic spine. With the advent of endoscopy, reaching the thoracic spine has become technically more challenging, but safer and more effective for the patient. Thoracoscopy was first utilized in the spine in 1910 by Jacobaeus to diagnose and lyse tuberculous adhesions in the lung [1, 2]. Since then, laparoscopy was used extensively in the 1980s to perform cholecystectomies [3]. The advantages of laparoscopy included a reduction in postoperative pain, hospital stay, and recovery time, with a quicker return to work. This success led to the increased interest in and use of minimally invasive techniques in the treatment of thoracic disorders. In the early 1990s, video-assisted thoracoscopic surgery (VATS) was used with increasing frequency to treat various pulmonary conditions. This included treating pleural effusions [1, 4] and recurrent spontaneous pneumothoraces [5], obtaining lung biopsies in patients with interstitial lung disease [6] or indeterminate pulmonary nodules [7], and evaluating mediastinal adenopathy [8]. As with the laparoscopic outcomes, the thoracoscopic technique was associated with the same positive findings, with a distinct advantage when compared to an open procedure through a thoracotomy [9, 10]. Because rib resection and/or the spreading of ribs associated with an open thoracotomy procedure is avoided when performing VATS, there is less immediate postoperative incisional pain [9, 10]. There is also a decreased incidence of chronic postthoracotomy pain and fewer postoperative respiratory difficulties, including lower chest tube output and less shoulder girdle dysfunction [9, 10]. There are less blood loss, a lower risk of infection from a smaller incision, and a cosmetically favorable scar from three to four small portal sites [11]. There is a shorter hospital stay, the technique is less costly, recovery time is faster, and patients return to work faster. Complications are rare, with intercostal neuralgia and atelectasis being the most common [9, 10]. There have been great strides in the use of VATS in treating spinal disorders. Obenchain reported the first anterior laparoscopic lumbar discectomy in 1991 [12]. In 1993, Mack and Regan initially reported on the application of thoracoscopic techniques in the thoracic spine [12–15]. They performed VATS on various conditions, including the drainage of spinal abscesses, biopsy of veterbral bodies, discectomy for a herniated nucleus pulposus, and anterior releases for kyphoscoliosis [12–14, 16, 17]. More recently, in 1995, McAfee et al. reported good results with the use of VATS in performing thoracic corpectomies for spinal cord decompression [16, 18]. In 1998, Regan et al. reported outcomes on the excision of thoracic disc herniations with a 12- to 24-month follow-up [17, 19]. They found that VATS resulted in a shorter hospitalization, less postoperative narcotic use, and an early recovery time in the treatment of spinal conditions. There was a 75.8% satisfactory outcome, with relief of radicular and myelopathic symptoms. They did report a 13.8% complication rate, including excessive bleeding, atelectasis, pleural effusions, and diaphragm perforation.

Technique

VATS on the spine should be performed in a standard operating room. A modification from the standard spinal surgery setup is required. Double-lumen endotracheal tube placement is required, as one lung is deflated during the procedure, allowing visualization of the thoracic spine. The patient is positioned in the lateral decubitus position and secured. A right- or left-sided positioning is dependent upon the side of the herniation. The level being operated on should have a bolster placed underneath or a kidney rest. The upper leg is placed straight and the lower leg flexed. Both arms are flexed

R.B. Verma (✉)
Department of Orthopaedic Surgery, The Spine Institute;
Department of Neurosurgery, The Chiari Institute, North Shore Manhasset Hospital, Great Neck, NY 11021, USA
e-mail: rohitvermamd@yahoo.com; verma_01@yahoo.com

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to 90°. The operating table should be capable of Trendelenburg or reverse Trendelenburg positions in order to allow the deflated lung to fall away from the spine to increase visualization and decrease inadvertent injury during the procedure. A wide sterile preparation is made involving the axilla to below the iliac crest and from sternum to the spinous processes to allow for a conversion to an open thoracotomy if necessary.

Equipment includes the usual setup for a standard thoracoscopic procedure. This includes telescopes, cameras, illumination sources, monitors, trocars, vascular clipping devices, graspers, retractors, bipolar, electric cauteries, and harmonic scalpels (Figs. 6.1 and 6.2). The 30°-angled 10-mm telescope is used almost exclusively for spinal procedures. It allows the safe passage of an instrument behind a structure at various angles and with proper visualization. Recently, using a 5-mm telescope with improved optics and high-definition monitors allowed even smaller incisions.

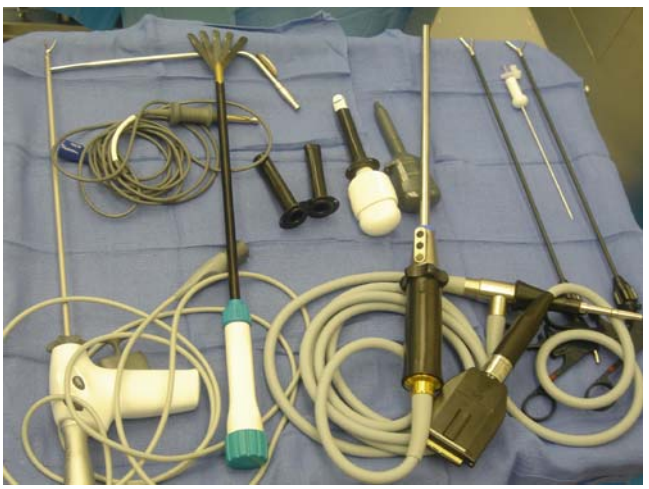

Fig. 6.1 From left to right: harmonic scalpel, fan retractor, trocars, 30°-angled scope, and graspers

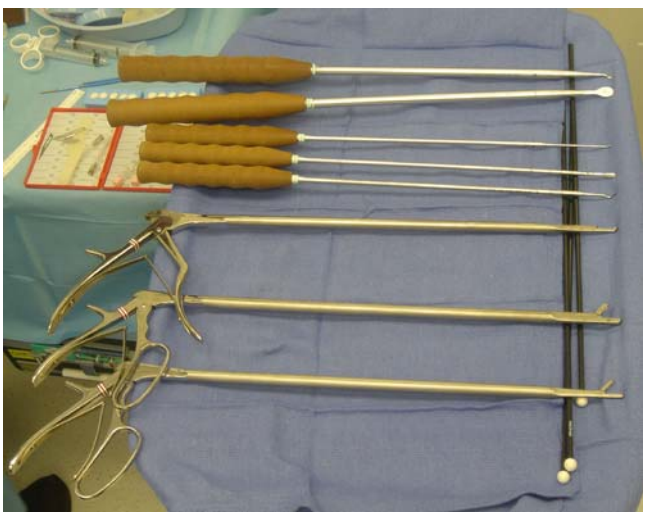

Fig. 6.2 Curettes, kerrisons, and pituitary rongeurs

The spine surgeon stands on the abdominal side of the patient across from the video monitor. The first assistant stands on the opposite side of the patient and faces an opposing second monitor. The second assistant, if necessary, stands on the same side as the spine surgeon (Fig. 6.3).

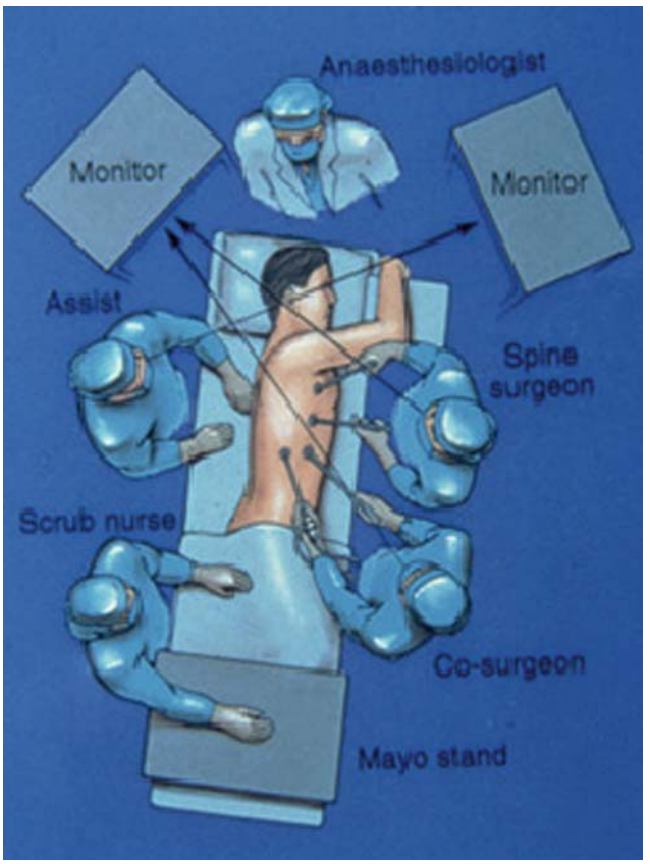

Fig. 6.3 Setup for VATS

Localization of the level being operated on is performed under fluoroscopy or via X-rays, in this case T9-T10 (Fig. 6.4). Preoperative thoracic and lumbar films are taken to obtain an accurate rib count. After sterile preparation and draping, the first portal site incision is made directly over the localized area in the midaxillary line between the ribs. Following that, blunt dissection using tonsil clamps is performed until reaching the muscular layer between the ribs. At this point, the ipsilateral lung is collapsed and the chest cavity is entered bluntly with a clamp. The portals are established using introducers. Two or three other portals are established anteriorly, superiorly, and inferiorly. These are used as working and retracting portals. These are placed under direct visualization using the thorascope through the first portal. In general, these portals are several inches away from the first portal in order to have adequate working space for the instruments placed through these portals. This will avoid fencing of instruments, which occurs when portals are placed too

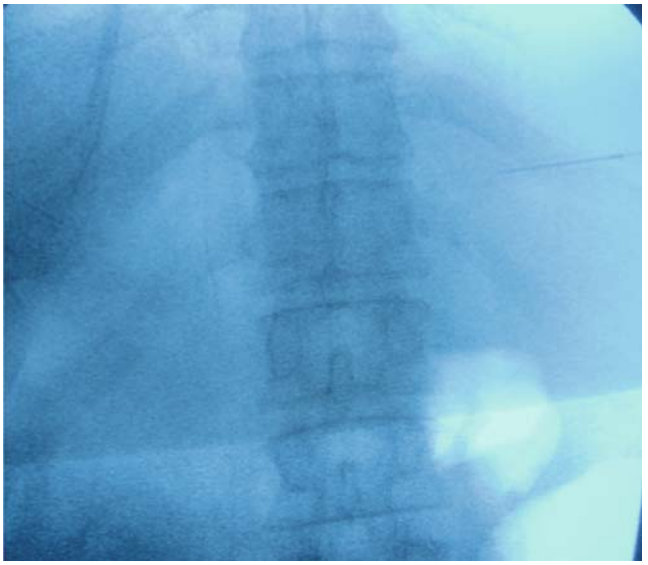

Fig. 6.4 Localization of the level prior to surgery is performed with a spinal needle

close to each other. The lung, although deflated, can still sometimes hinder access to the spine. A fan retractor or lung clamp can be used to retract the lung. Tilting the table 15–30° toward the spine surgeon and placing the patient in Trendelenberg or reverse Trendelenberg position depending on location of the surgery can improve visualization.

Intraoperative localization for the correct disc space is done with a bent 18-gauge spinal needle under fluoroscopy. After localization, the pleura is divided above and below the disc space with a harmonic scalpel and extended to the rib head covering the disc. Segmental vessels may transverse the disc space; if so, bipolar, endoscopic clips or the harmonic scalpel may be used to ligate the vessels (Fig. 6.5).

After exposing the rib 2–3 cm proximally, a rib cutter is utilized to resect it. The costovertebral ligaments tether the rib to the vertebral body and are difficult to release.

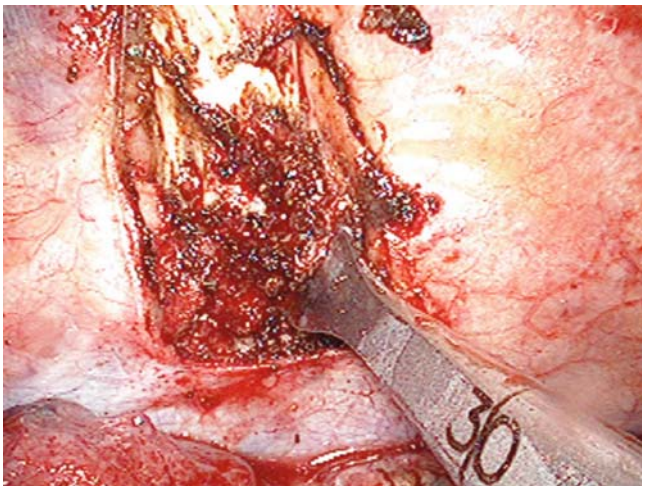

Fig. 6.5 Pleura is divided; rib, disc, and endplates are exposed

Curettes, cautery, and/or sharp dissection can be utilized to release the rib head. The rib head is then removed from the chest cavity and morselized for use later as autograft in fusion (Figs. 6.6-6.8). Alternatively, the rib head can be drilled away using a coarse diamond-tipped burr. The disc space is then delineated using the harmonic scalpel.

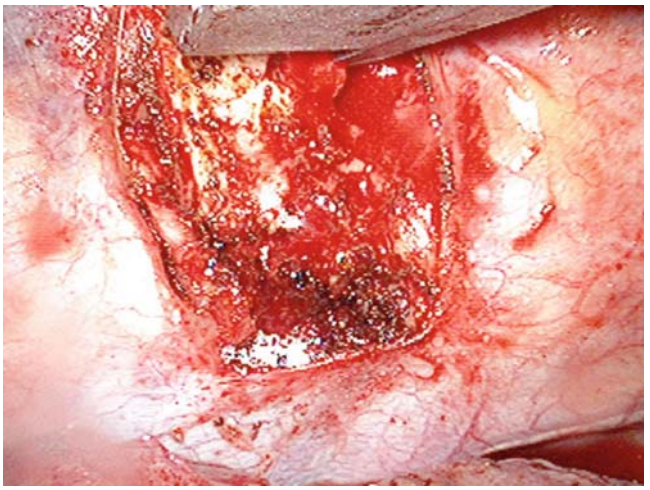

Fig. 6.6 Rib is exposed and resected with rib cutter

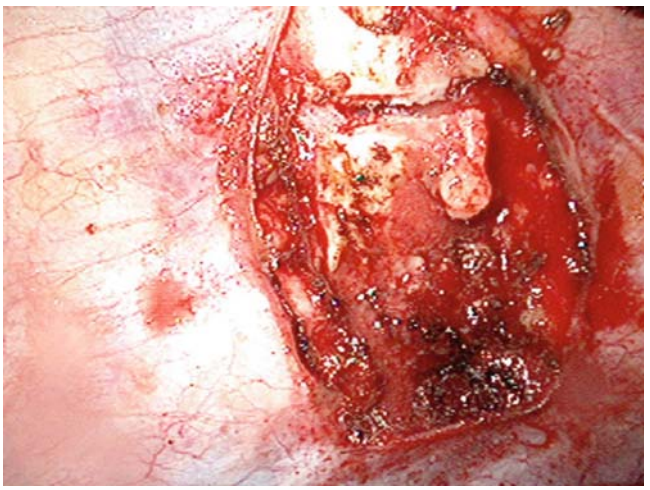

Fig. 6.7 Rib head and proximal 2.5-cm rib are resected

Vertebrectomy above and below the disc space is performed using a high-speed diamond burr. Approximately 4 mm of bone is burred above and below the disc space (Figs. 6.9 and 6.10). The depth depends upon where the pathology is located (lateral, posterolateral, or central). The location should be confirmed on preoperative MRI or CT scan. After vertebrectomy, the discectomy is carried out using angled curettes, kerrison, and pituitary (Fig. 6.11). This creates a trough and gives access to the spinal canal (Fig. 6.12). The remainder of the disc, posterior endplate, osteophytes, and/or PLL is resected with kerrison, pituitary rongeur, and curette. Fine curettes can be used to resect the remaining bone

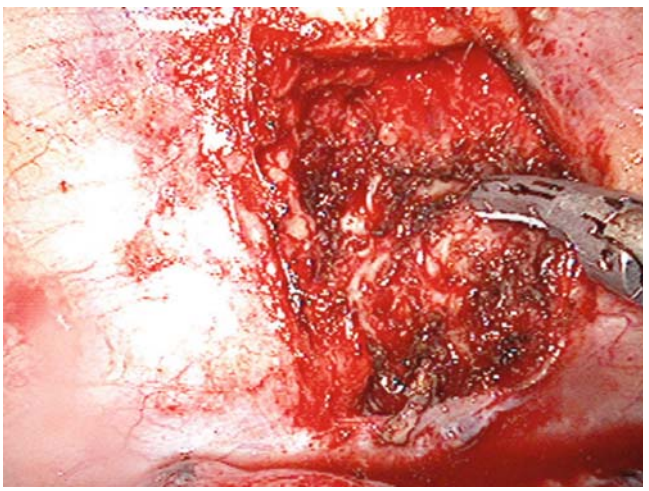

Fig. 6.8 View of remaining spinal articular facet following rib head resection

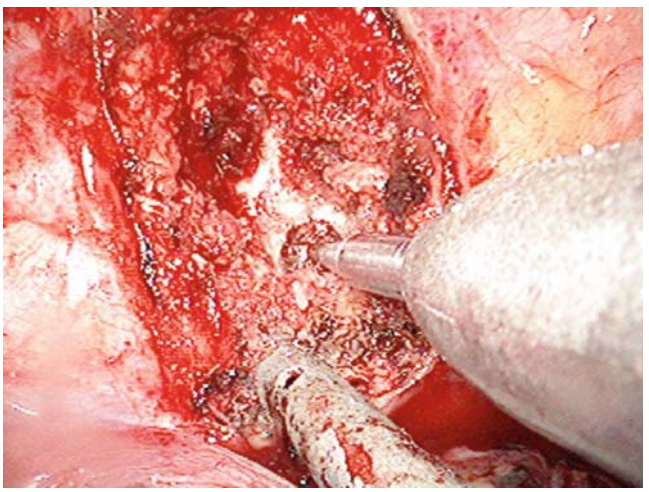

Fig. 6.9 A coarse diamond-tipped burr is used to resect the vertebral body adjacent to the disc

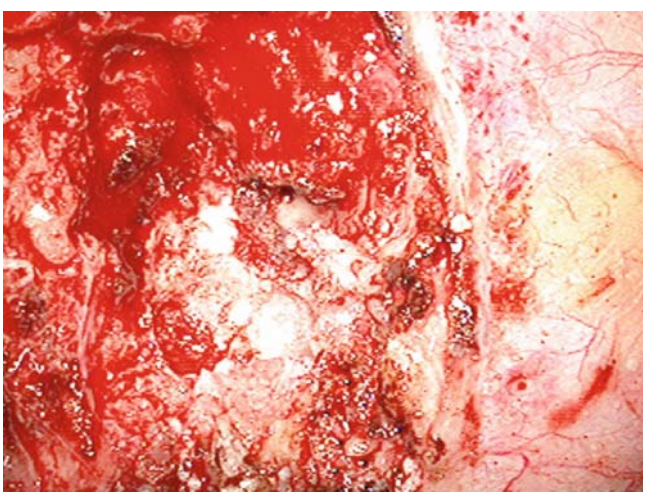

Fig. 6.10 Further resection of posterior vertebrae above and below disc

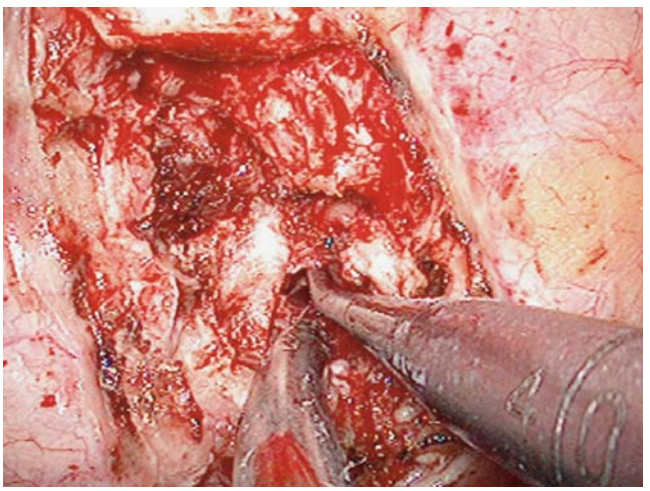

Fig. 6.11 Disc is excised using curettes, pituitary, and kerrisons

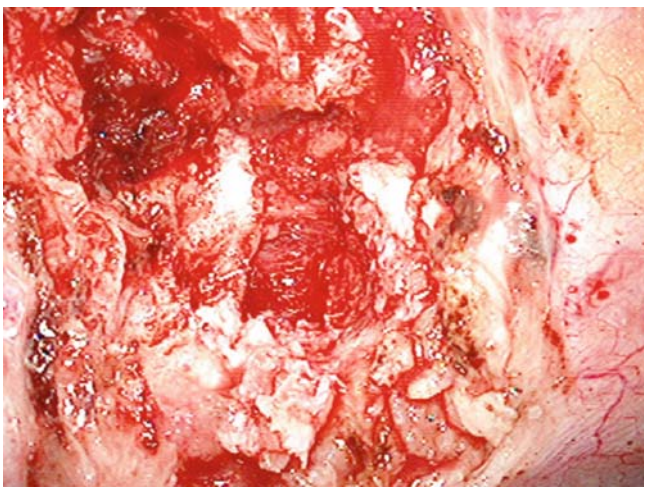

Fig. 6.12 Thoracic disc is excised adjacent to the canal

and soft tissue composed of herniated disc material, calcified disc, PLL, and/or posterior annulus on the dura (Figs. 6.13-6.16). In the case of ossified or calcified disc adherent to the dura, freeing the adherent calcified disc from surrounding tissue may sometimes allow decompression to occur without risking a dural tear and spinal fluid leak.

The determination of spinal fusion in thoracic disc surgery can be made before surgery in cases of discogenic pain or during surgery if extensive bony resection results in instability. In the case of lateral herniation with radicular pain, fusion may not be necessary if minimal bone resection is done. In the case of central herniation, a large trough is often created, which may require fusion and instrumentation. In the case of paracentral herniations, it depends on how much bone is resected. To fuse the two vertebral bodies, a combination of the morselized rib autograft cortical allograft or PEEK interbody devices are used (Fig. 6.17). Anterior vertebral body screws with staples and a connecting rod are sufficient in most cases to support the interbody fusion graft (Fig. 6.17). Final fluoroscopic

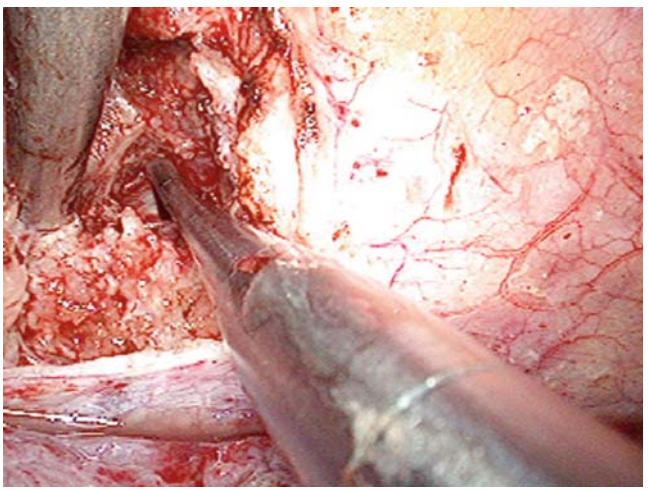

Fig. 6.13 Angled probe used to develop plane between dura and herniated disc

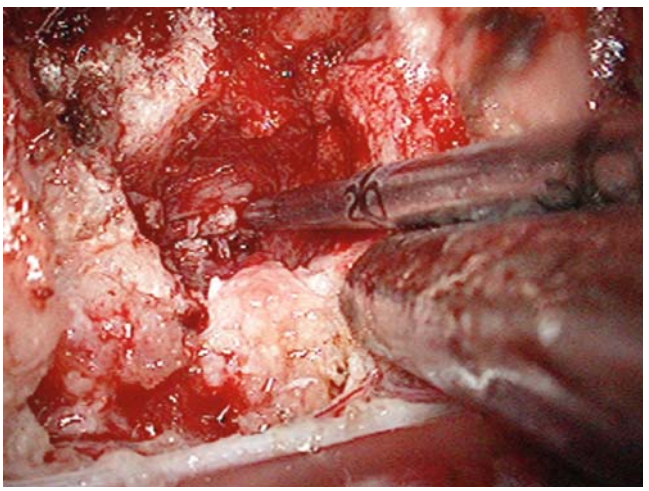

Fig. 6.14 Removal of herniated disc fragments using angled dental-tipped probe

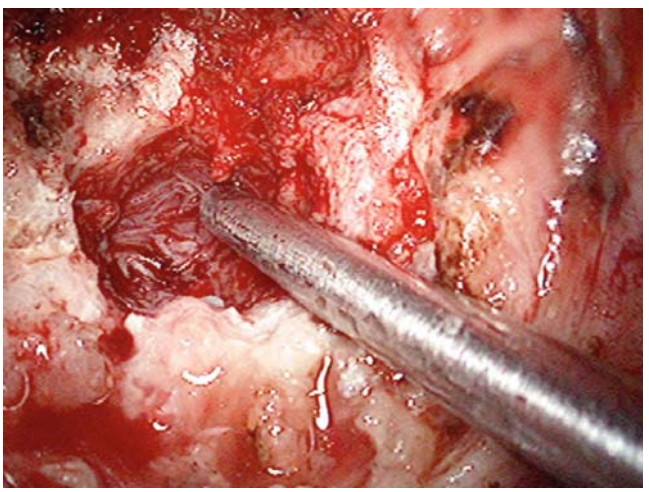

Fig. 6.15 Resection of posterior longitudinal ligament to access sequestered disc fragments

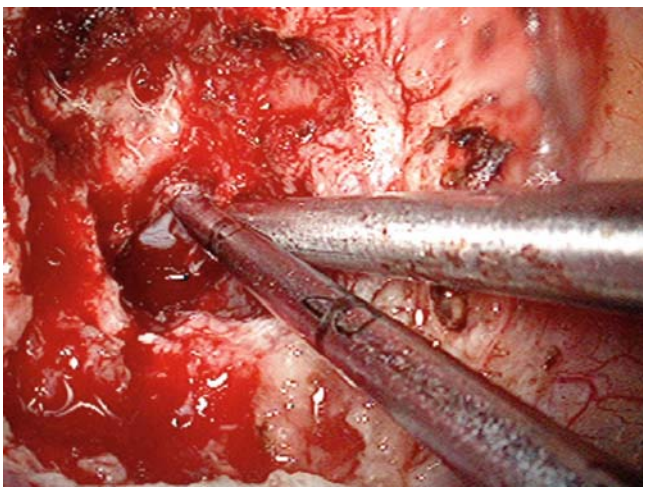

Fig. 6.16 Exposure of dura after disc herniation has been removed

images are obtained to ensure excellent alignment and position of the hardware and graft. Prior to closing all the incisions, a chest tube is placed under direct thorascopic visualization.

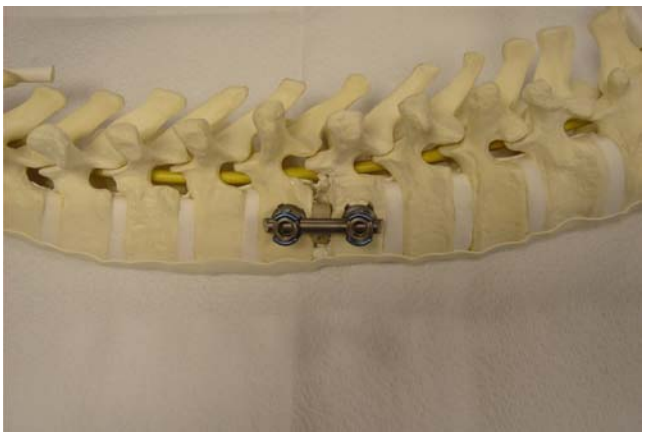

Fig. 6.17 Saw bones model illustrating PEEK interbody device and Alphatec staple and vertebral body instrumentation (reprinted with permission from Alphatec Spine, Inc.)

The patient usually spends one day in the ICU and is then transferred to the floor. The chest tube is left in place for at least one day and removed when the drainage is less than 100 cc per shift. Radiographs of the chest are obtained and evaluated for pneumothoraces after removal of the chest tube. The patient is usually discharged on postoperative day 4 or 5 barring any complications. The patient will then follow up in the office at the one-week, three-week, six-week, three-month, six-month, and one-year marks.

Case 1

Fifty-seven-year-old female with history of radicular pain down both extremities with coughing, sneezing, and

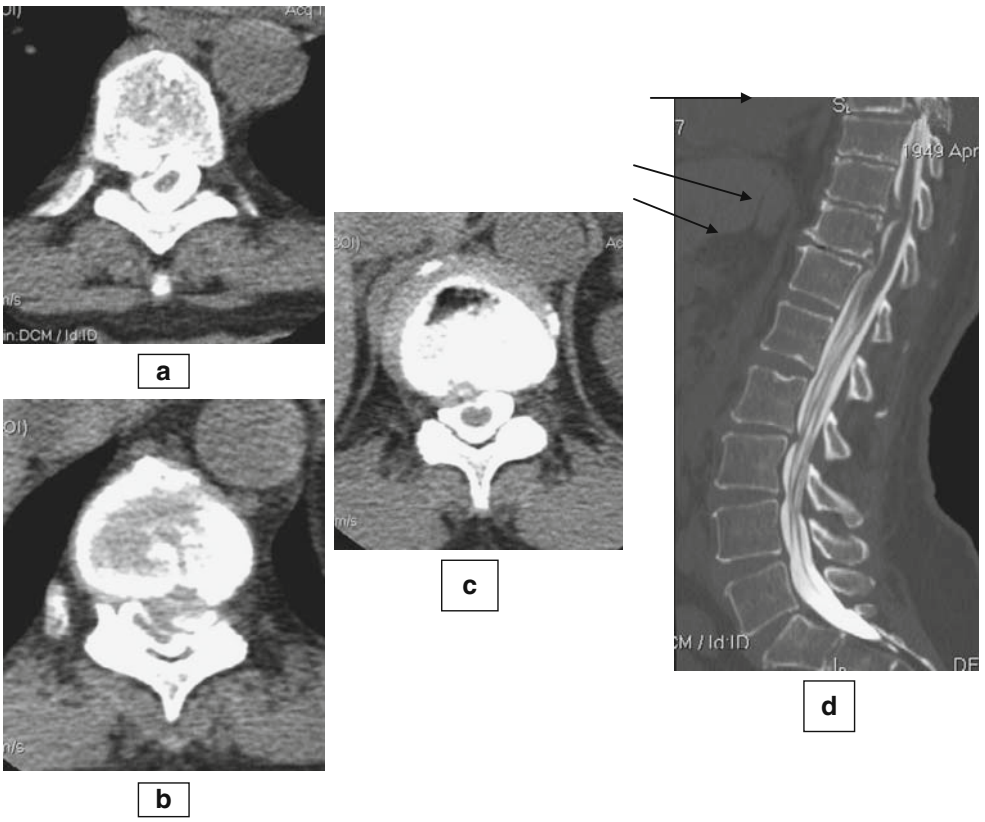

Fig. 6.18 CT myelogram of a 57-year-old female with calcified thoracic disc herniations at (**a**) right T8-T9, (**b**) right T11-T12, (**c**) left T10-T11. (**d**) The three herniations on the sagittal cuts, which are large enough that all three can be viewed on a midline cut

straining during bowel movements and difficulty with ambulation. On physical exam she has increased reflexes in the Achilles tendon and patellar tendon. Imaging studies on CT myelogram scan show a (1) T8-T9 large right lateral partially calcified disk herniation impinging on the right side of the cord, (2) T10-T11 large left lateral herniation causing severe spinal stenosis, and (3) T11-T12 moderate-sized right lateral disc herniation with mass effect on the thecal sac (Fig. 6.18). The patient underwent a staged procedure with a right-sided VATS at T8-T9 (Figs. 6.19-6.21), fusion using rib autograft and allograft (Fig. 6.22), followed by Anterior Spinal Fixation (Fig. 6.23). One week later the patient underwent a VATS at T10-T11 with fusion using rib allograft on the left side. The patient tolerated both procedures and at follow-up had resolution of all her symptoms (Fig. 6.24). At three months the patient is off all medications and is work-ready.

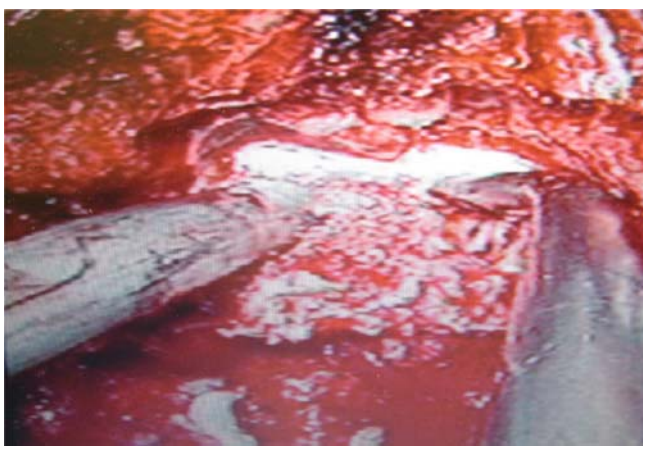

Fig. 6.19 Release of adherent calcified disc at T10-T11 using an angled curette and dental tool

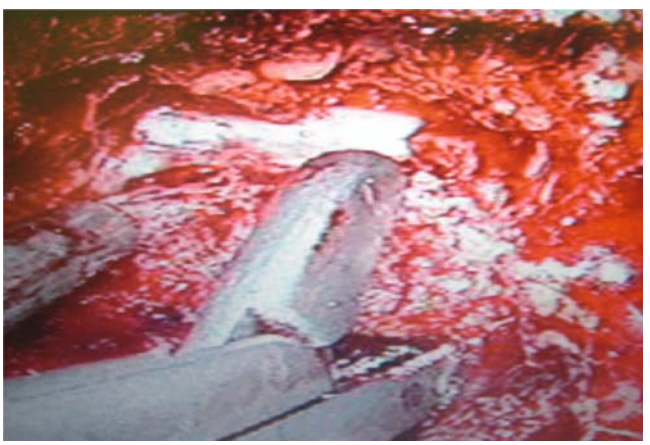

Fig. 6.20 After releasing the calcified disc, a pituitary rongeur is used to excise the disc

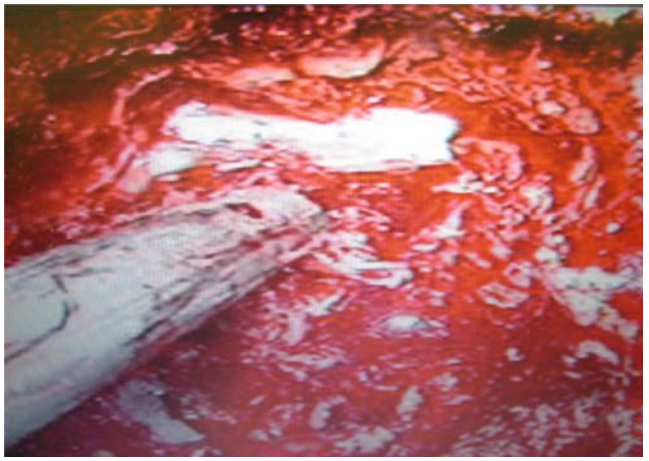

Fig. 6.21 This shows the dura after resection of the calcified disc. Note that there is extensive bony resection in order to obtain an adequate decompression. This will require an interbody device along with Anterior Spinal Fixation

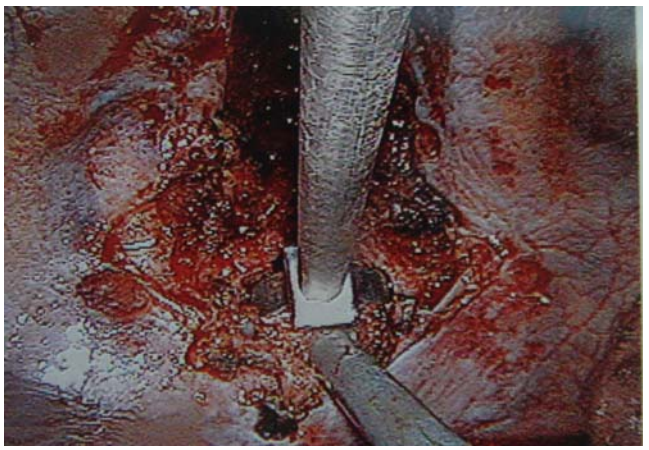

Fig. 6.22 Placement of rib allograft and autograft

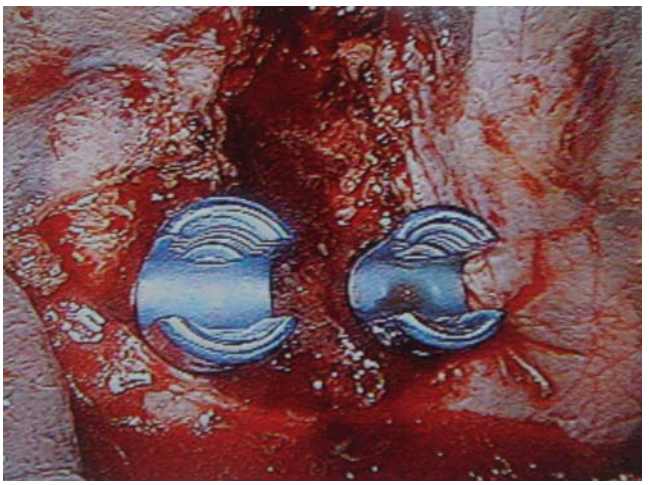

Fig. 6.23 Alphatec staple system with vertebral body screws used for Anterior Spinal Fixation (reprinted with permission from Alphatec Spine, Inc.)

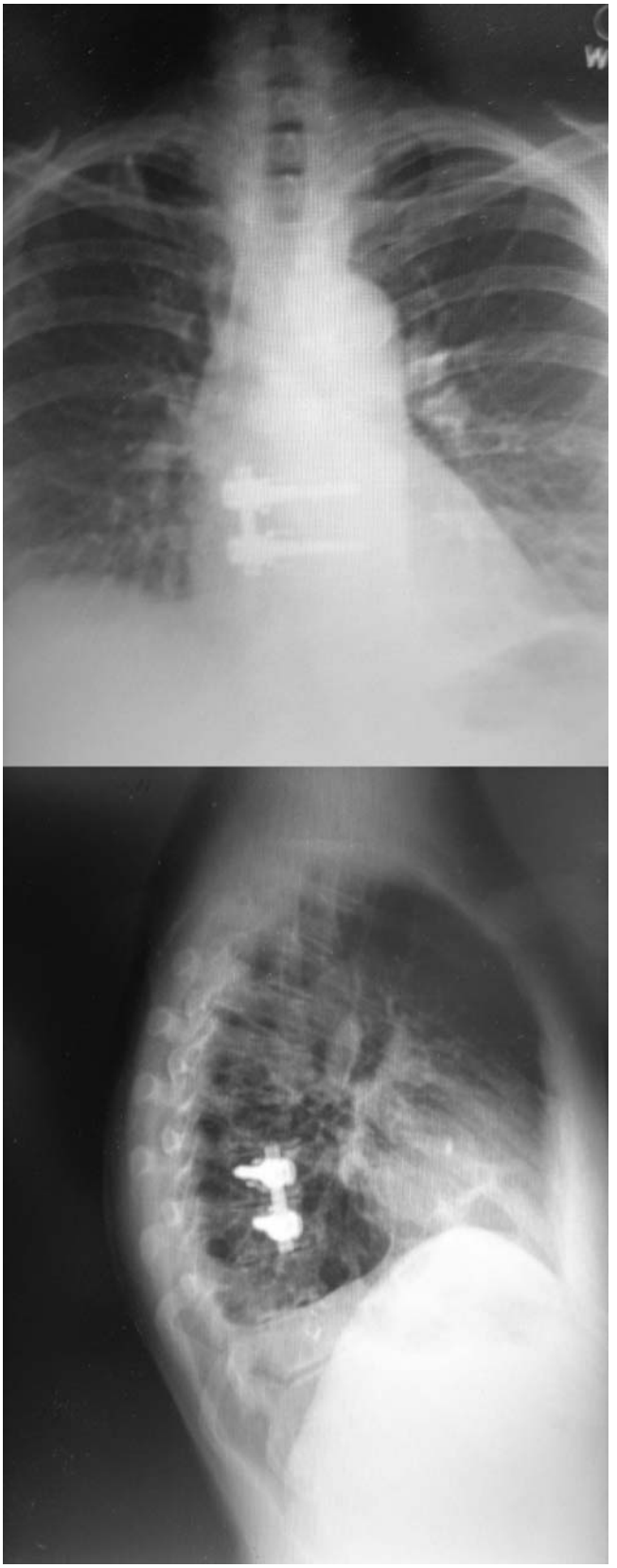

Fig. 6.24 Postoperative AP and lateral X-rays showing the hardware to be in excellent position and no evidence of pleural effusions or pneumothoraces

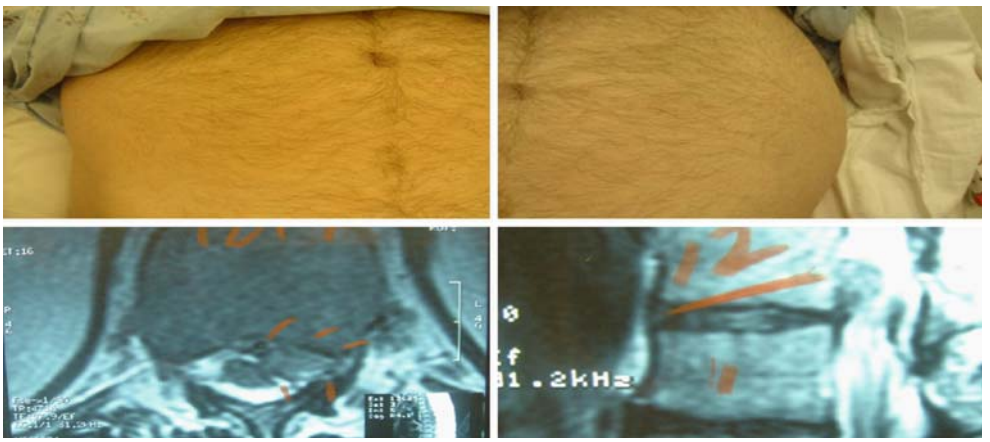

Fig. 6.25 MRI of a 45-year-old male with a T12-L1 thoracic disc herniation presenting with radicular pain along the left abdominal wall and flaccid abdominal muscles

Case 2

Forty-five-year-old male who has pain along his left abdominal wall for the past two years and a recent onset of outpouching of his abdominal wall. He has been worked up for kidney stones and MI prior to presenting to the authors. On physical exam the patient has a flaccid abdominal wall on the left, three beats of clonus bilaterally, and increased reflexes in the patellar tendon and Achilles tendon bilaterally. The patient has a left-sided T12-L1 thoracic disc herniation. The patient underwent a left-sided VATS without a fusion. The patient tolerated the procedure, and postoperatively his symptoms subsided (Fig. 6.25).

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Thoracic and Lumbar Kyphoplasty

7

Christopher M. Bono and Steven R. Garfin

Introduction

Techniques of percutaneous vertebral body augmentation have been developed to stabilize osteoporotic thoracic and lumbar compression fractures. Current methods include vertebroplasty and kyphoplasty [1–5]. Distinct from vertebroplasty, kyphoplasty involves the percutaneous insertion of an inflatable balloon tamp into the vertebral body to create a void in which viscous cement is inserted under low pressure. The balloon tamp also enables vertebral body height restoration. In a number of clinical studies [3, 4, 6, 7], kyphoplasty has demonstrated a marked effectiveness in pain relief from symptomatic osteoporotic thoracic and lumbar compression fractures. In addition, the technique has been shown to be useful in the management of painful lytic neoplastic bone lesions [8–10]. Despite these good results, the success of kyphoplasty in general practice depends on a clear understanding of its indications, technique, and complications.

Indications

Treatment of Osteoporotic Fractures

Treatment of osteoporotic vertebral compression fractures (VCFs) is the primary indication for kyphoplasty. It is indicated in those patients with progressive, intractable, or nonresolving pain associated with an acute or subacute VCF in the thoracic or lumbar spine. The exact mechanism by which it decreases pain is not clearly understood. Most speculate that it is the result of the hardened cement's effect to stabilize the fractured fragments. Less popular theories purport that the exothermic reaction during cement curing might lead to nociceptive denervation within the bone. However, cementing techniques, using nonexothermic compounds, also provide relief, so it is most likely the initial stabilization that leads to pain relief, not heat denervation. The procedure has consistently resulted in pain relief in 90% or more of cases [3, 4, 6, 7].

The concomitant presence of thoracic or lumbar back pain and a vertebral compression fracture is not by itself an indication for kyphoplasty. Obtaining objective evidence that the vertebrae in question are the cause of pain is critical. The practitioner should not reflexively assume that back pain in an elderly patient must be coming from a VCF detected on a radiograph. Amid various other causes of pain, elderly patients are often symptomatic from degenerative disorders such as facet arthritis, stenosis, spinal deformities, or other, more serious causes. In most cases, the primary source of pain can be determined by a careful history and physical examination.

The authors' clinical criterion for performing a kyphoplasty can be summarized as point tenderness upon percussion or palpation of the spinous processes of acutely or subacutely fractured levels as determined by radiographic imaging studies. With the use of a radiopaque marker, plain radiographs can help correlate the site of pain and tenderness to a fractured level. Beyond this maneuver, however, they are not useful in determining the acuity of the injury or the effects of the fracture on the spinal canal. In the authors' practice, a magnetic resonance imaging (MRI) study is obtained, when possible, to determine which vertebral bodies demonstrate bone edema, an indication that the fracture is recent. T1-weighted (Fig. 7.1) and STIR (short-tau inversion recovery) images are most useful in detecting intraosseous bone edema, with the former demonstrating a decreased signal and the latter demonstrating an increased signal intensity often lasting for six months from the time of injury. Exploiting the so-called myelography effect of the cerebrospinal fluid's bright signal, T2-weighted images are useful in assessing the relationship of the fractured fragments to the spinal canal and neural elements.

C.M. Bono (✉)
Department of Orthopaedic Surgery, Boston Medical Center, Boston University School of Medicine, Boston, MA 02118, USA
e-mail: bonocm@prodigy.net

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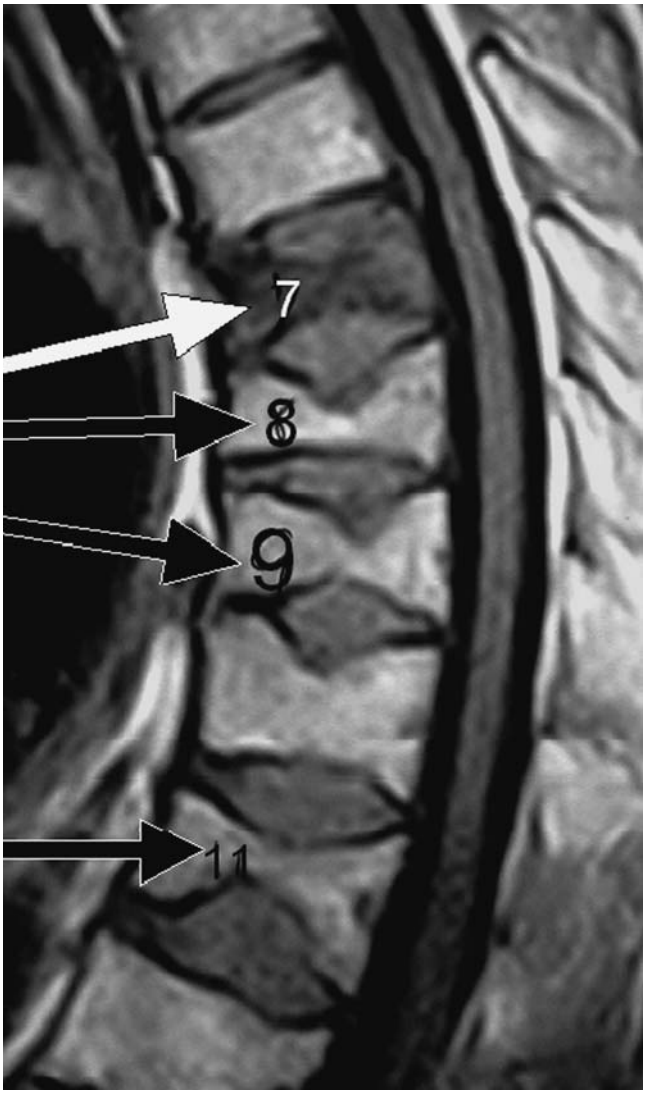

Fig. 7.1 In this T1-weighted sagittal MR image, an acute fracture of T7 (*white arrow*) can be easily distinguished from more chronic fractures of T8, T9, and T11 (*black arrows*) by the hypointense signal, which represents bone edema

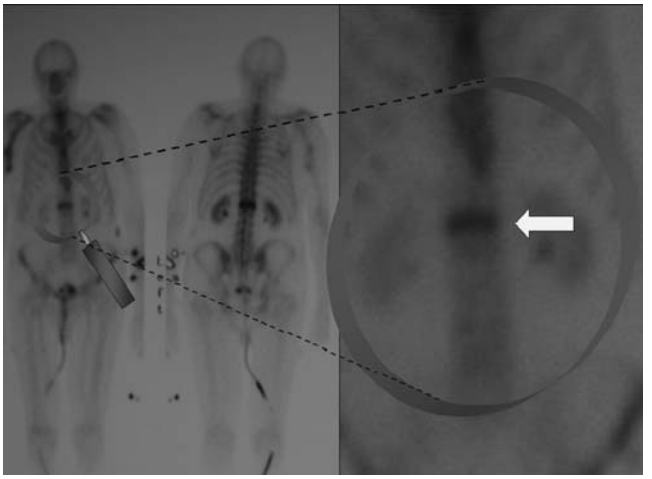

Fig. 7.2 A bone scan is a useful alternative to MRI for determining the fracture acuity. In the image shown, an acute fracture of L1 is noted by its markedly increased uptake (*white arrow*) compared to the adjacent vertebrae

A bone scan can also be used to determine the fracture acuity (Fig. 7.2). This study, combined with a computerized tomogram (CT) through the fractured region, is a reasonable alternative to MRI. Though it does not indicate the fracture's acuity, the CT should be obtained to detect fracture fragment retropulsion into the spinal canal, which can be a relative contraindication to the procedure.

Contraindications. Kyphoplasty should not be attempted in healed, nonpainful fractures that do not demonstrate increased uptake on a bone scan or edema on an MRI. The technique should not be employed in the presence of a local infection. Some associated medical problems, such as obstructive pulmonary disorders, can make prone positioning difficult if not dangerous. Though not optimal, the authors' have performed kyphoplasty with a patient in a lateral or oblique position in such settings. Other disorders, such as uncorrectable coagulopathies, can lead to epidural hematoma formation, particularly if the pedicle borders or posterior vertebral body margin has been violated. A technical contraindication to kyphoplasty is the inability to adequately visualize the fractured segment with intraoperative fluoroscopic imaging. This is often the case with fractures above T5. Another technical contraindication is the presence of severe vertebral plana in which the pedicles do not allow safe entry into the vertebral body. In the authors' practice, osteoporotic burst fractures with fragment retropulsion into the spinal canal is a relative contraindication; some surgeons, however, have found kyphoplasty to be safe and effective in select cases with this condition.

Treatment of Lytic Neoplastic Lesions

A recently burgeoning indication for kyphoplasty is in the treatment of painful lytic and some blastic vertebral body lesions caused by neoplastic disorders such as multiple myeloma and metastatic cancer (Fig. 7.3). Several reports have shown fair rates of pain relief with kyphoplasty for neoplastic lesions [8, 11, 12]. Similar physical examination criteria are used in the evaluation of such patients, with pain and tenderness correlating to the level of the detected lesion being a reasonable indication for the procedure. Importantly, the evaluation of cancer patients should adhere to standard oncological protocols, which include appropriate laboratories, chest, abdominal, and pelvic

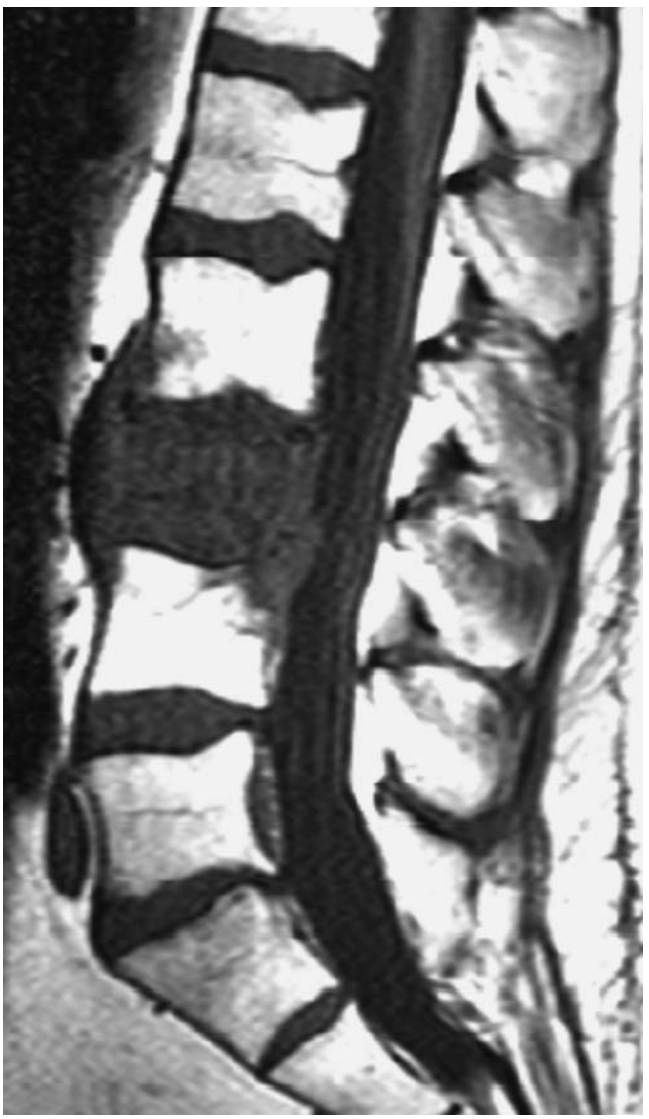

Fig. 7.3 Though it is not a definitive diagnostic test, MRI can also be useful in distinguishing metastatic lesions from osteoporotic compression fractures. In the above image, a homogeneously hypointense signal with some extension beyond the borders of the vertebral body is noted, which is characteristic of a metastatic lesion

CT, full body bone scan, and MRI of the spinal region in question. Ideally, confirmation of the diagnosis from tissue biopsy of the primary or most accessible metastatic lesion should be established prior to performing a kyphoplasty. If a tissue diagnosis has not been made, an intraoperative frozen section or preoperatively obtained percutaneous biopsy of the vertebral lesion should be analyzed prior to cement insertion. This is especially important if the decision to perform kyphoplasty will be influenced by the biopsy results. This can be the case for a primary bone tumor in which en bloc resection might be preferable.

Contraindications. In addition to those technical contraindications discussed above for VCFs, extension of tumor material into the epidural space or signs of neural compression are considered relative contraindications to kyphoplasty. The source of the primary cancer is also important to consider, as some, such as renal cell carcinoma, are hypervascular and can lead to uncontrollable hemorrhage with bone cannulation. Though it would not be the authors' preference to perform kyphoplasty in this situation, preoperative arteriography with feeder vessel embolization should be considered prior to the procedure.

Equipment

The necessary equipment to perform kyphoplasty includes

- Radiolucent operating table
- One or two fluoroscopic image intensifiers (C-arms)
- Jamshidi needle
- Smooth or sharp-tipped guidewires
- Combination dilator-working cannula
- Bone biopsy device (if indicated)
- Hand-twist drill bit
- Inflatable balloon tamp
- Radiopaque dye
- Cement mixer
- Cement preparation (polymethylmethacrylate cement mixed with contrast).

Setup

Anesthesia

Either a general or local anesthesia technique can be used. It is the authors' preference to utilize general anesthesia. In contrast to using local with sedation, under general anesthesia, the patient does not move during the procedure, which can lead to instrument misplacement or compromise of the fluoroscopic views. It may also be more appropriate for patients undergoing multiple levels of kyphoplasty. Rarely, general anesthesia is contraindicated because of medical comorbidities, in which case local anesthesia is preferred.

Positioning

If local anesthesia is elected, patients can comfortably position themselves prone on the operating table before the sedative is infused. When possible, transverse chest

and thigh rolls should be used to extend the spine and help reduce the fracture, though this may be uncomfortable for awake patients.

If general anesthesia is used, the patient is carefully log-rolled into the prone position onto the table after the endotracheal tube has been secured. The neck should be maintained in a neutral position at all times. To allow unobstructed movement of the image intensifiers, the patient's arms are placed at his or her sides. They should be well padded. A sheet can be tucked underneath the pelvis to secure them in place. However, for treatment below T11 or T12, the upper extremities may be flexed up on arm boards.

It is the authors' preference to use two C-arms. This enables the surgeon to obtain simultaneous orthogonal views of the spine. Furthermore, the C-arms do not have to be moved between the anteroposterior (AP) and lateral positions, as is the case if one machine is utilized. Adequate identification of the operative levels and visualization of all bony landmarks should be ensured prior to starting the procedure. The pedicle and vertebral body margins should be clearly seen on both the AP and lateral views. A true AP view should be confirmed by seeing the spinous processes end-on and equidistant from the right and left pedicles. This is sometimes challenging in patients with substantial scoliotic deformity or profound osteopenia. In the lateral view, the pedicle shadows should overlay each other, as close as possible, to avoid image parallax error. The anterior vertebral body border should be clearly seen on the lateral view. Oftentimes, the patient's arms must be repositioned more anterior to clarify this view. Endplates should be clear, with no obliquity if possible.

In the final stages of positioning, the knees should be well padded and flexed to about 20° to relieve tension on the sciatic nerves. The patient should be secured to the table with a belt. The surgical sites should be marked using the C-arms, and the area prepped and draped in the usual sterile manner.

Technique Description

Vertebral Body Cannulation: Placement of the Jamshidi Needle

The first step of kyphoplasty is the placement of the Jamshidi needle. This is a cannulated device, originally developed for percutaneous bone biopsy. Correct positioning of the Jamshidi is critical, as it establishes the trajectory of the working cannula, drill bit, and balloon.

Transpedicular Approach

A transpedicular approach can be used at any level in which the transverse pedicle diameter is large enough to accept the working cannula. Most upper thoracic pedicles, as well as some lumbar ones, are too small to safely accept the kyphoplasty tools. This determination should be made prior to surgery by making preoperative measurements on axial MRI or CT images. The transpedicular approach enables bilateral cannulation of the vertebral body.

Using the tip of the Jamshidi needle, AP and lateral views are taken to determine and mark the optimal skin entry site for the instruments. In the AP view, this is just lateral and superior to the lateral border of the pedicle. In the lateral view, the mark should be aligned with a trajectory that passes within the mid-aspect of the pedicle.

The Jamshidi needle is then introduced percutaneously through the skin at this site. Aiming about 10° medial, the tool is gently passed through the paraspinal muscles until the cortical surface of the posterior elements is encountered. The tip of the needle is then walked on the bone until it is located at the lateral pedicle border on the AP view and aligned within the mid-aspect of the pedicle on the lateral view. With gentle downward pressure, the needle is advanced until it starts to engage the osteoporotic bone. At this time, the starting point on the bone is confirmed by fluoroscopy.

Using frequent images to watch the needle tip, it is slowly advanced into the bone. Images must confirm the proper trajectory. To achieve optimal positioning of the balloon tamp, the needle should be angled toward the midline. Care should be taken to avoid exaggeration of this trajectory to prevent breach of the medial pedicle wall. For optimal security, the needle tip should not extend beyond the medial border of the pedicle on the AP view until it reaches the posterior vertebral body cortex on the lateral view (Fig. 7.4). If medial breach is suspected, an *en face* view can be obtained to better demonstrate the position of the needle within the pedicle.

The Jamshidi needle can be cranially or caudally targeted toward a particular region of the vertebral body. Because of the compression deformity of the vertebral body, the starting point of the needle largely determines the range of trajectories possible during the final placement. With compression of the superior endplate, the tool is directed toward the inferior half. Conversely, the needle is directed toward the superior half of the vertebral body with compression fractures of the inferior endplate. If the vertebra is uniformly compressed, the tool is advanced toward the mid-body.

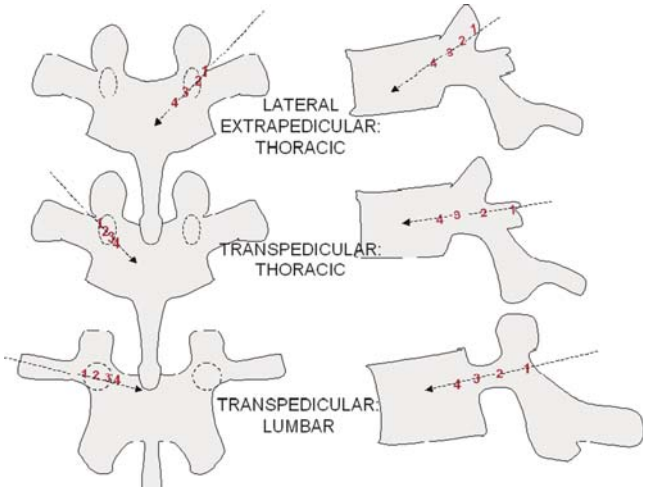

Fig. 7.4 Pictorial of trajectory "stopping points" to ensure safe placement of the Jamshidi needle

The transpedicular approach can endanger a number of important structures. The spinal cord or cauda equina can be injured with medial misplacement. The exiting nerve roots can be injured with superior or inferior misplacement. Anterior or anterolateral breach of the vertebral body can risk injury to the great vessels. Lateral misplacement endangers the lungs during thoracic-level procedures.

Lateral Extrapedicular Approach

The lateral extrapedicular approach is useful for those thoracic levels in which the pedicle is too small to contain the working cannula. It utilizes the rib and pedicle together, as a larger so-called effective pedicle (Fig. 7.5). By its nature, the lateral border of the pedicle is breached.

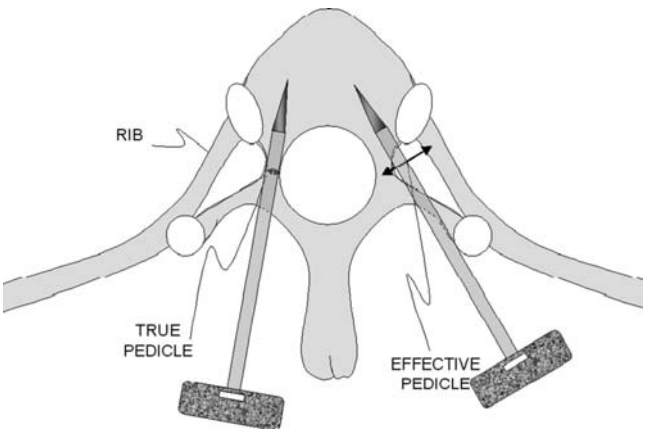

Fig. 7.5 The lateral extrapedicular approach utilizes the so-called effective pedicle, which is comprised of the rib-pedicle complex. The insertion site is more lateral using this approach compared to the transpedicular approach. The instrument must also be angulated more toward the midline to avoid lateral penetration of the vertebral body

The extrapedicular approach is not appropriate for lumbar vertebrae with small pedicles; such levels are better accessed using a posterolateral approach. Bilateral cannulation of the vertebral body can be performed using the extrapedicular approach.

Compared to the transpedicular approach, the needle trajectory is angulated more medial. Thus, the starting point on the skin is more lateral. The thoracic pedicles angle downward in comparison to the more straight-ahead configuration of the lumbar pedicles. This should be taken into consideration when marking the entry site.

The needle is pushed through the skin and passed through the paraspinal muscles. Once the posterior elements are felt, the needle tip should be directed toward the superolateral corner of the vertebral body on the AP view and within the mid-aspect of the pedicle on the lateral view. This enables the instrument to pass between the pedicle and the rib. The needle is carefully advanced into the bone with frequent images checked. As with the transpedicular approach, the needle tip should not extend beyond the medial border of the pedicle on the AP view until it has arrived at the posterior vertebral body margin on the lateral view (see Fig. 7.4).

With the more lateral starting position, the spinal cord is at less risk with the extrapedicular approach than with the transpedicular approach. By its nature, there is more risk of lateral penetration of the vertebral body, which may lead to parenchymal lung injury or pneumothorax.

Posterolateral Approach

The upper lumbar pedicles are often smaller than the lower thoracic vertebrae. If the transverse diameter is less than 4 or 5 mm, a transpedicular approach may not be advised. In these cases, the vertebral body can be accessed through its posterolateral cortex. The pedicle is not cannulated at any time with this technique. The starting point lies 8–10 cm lateral to the midline. The needle needs to be angled approximately 45° toward the midline, a trajectory similar to that used for discography.

The lateral view is more critical than the AP view when using the posterolateral approach. The needle tip should be anterior to the transverse process and neural foramen on the lateral view before it passes medial to the transverse process on the AP view. This helps avoid injury to the exiting nerve root. The needle tip should be engaging the junction of the posterior and middle thirds of the vertebral body on the lateral view and the lateral border of the vertebral body on the AP view simultaneously. The posterolateral approach is intended for unilateral balloon placement. Therefore, the needle should be advanced to the mid-vertebral body on the AP view to ensure adequate augmentation of the contralateral side.

Creating a Bone Void: Biopsy, Drilling, and Balloon Inflation

With the transpedicular and extrapedicular approaches, the Jamshidi needle is inserted just past the junction of the vertebral body and the pedicle on the lateral view (Fig. 7.6). The center stylet of the needle is removed, allowing insertion of a guidewire. It is the authors' preference to use a smooth guidewire. The wire is advanced until it can be seen extended beyond the tip of the Jamshidi needle. While the guidewire is held in place, the Jamshidi is removed with a gentle rotating motion. AP and lateral views should confirm maintenance of the guidewire's location.

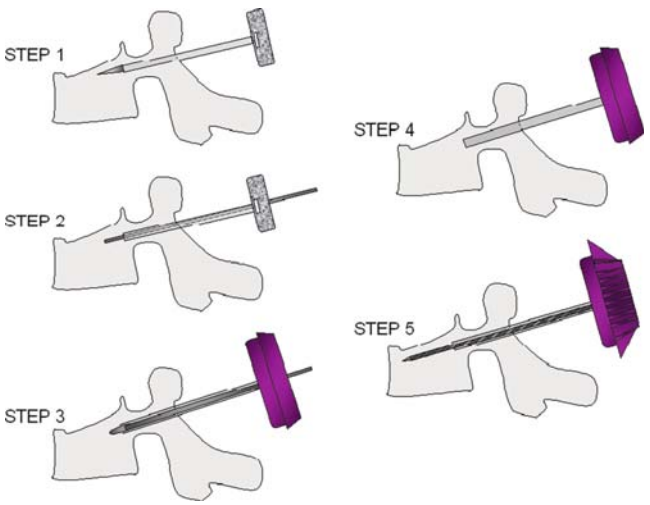

Fig. 7.6 (**Steps 1–5**) After the Jamshidi needle is confirmed to be in good position (**Step 1**), the central stylet is removed and replaced with a guidewire (**Step 2**). The Jamshidi needle is removed while holding the guidewire in place. A combination working cannula-dilator is inserted over the guidewire (**Step 3**). The guidewire and dilator can be removed, leaving the working cannula in place (**Step 4**). A twist-drill bit is advanced to within a few millimeters of the anterior vertebral body to create a space for the deflated balloon tamp (**Step 5**)

At this time, a small nick incision is made in the skin around the guidewire. A combination dilator and working cannula is then passed over the guidewire and advanced into the vertebral body. The tip of the dilator should be advanced just beyond the junction of the pedicle and the vertebral body. Lateral views should be checked periodically during this step, as the guidewire can be inadvertently advanced. Once the cannula-dilator is in its final position, the guidewire is removed. Next, the central dilator portion is disengaged and removed from the working cannula. Final adjustments of the working cannula can now be made.

If a biopsy is desired, it may be performed at this time. A biopsy tool can be inserted through the cannula and advanced into the vertebral body to cut a core of cancellous bone. Before it is removed, the device is rotated to help dissociate the biopsy bone from the remaining vertebral body. By placing a gloved finger over the open end of the device, a vacuum effect will be created to help maintain the core within the biopsy device. Alternatively, a small Luer-lock syringe can be attached to the biopsy device, and the plunger pulled back to create a vacuum during removal. After removal, a central pusher is used to retrieve the bone specimen, which is then sent for pathological evaluation.

Next, a finger-controlled twist drill is introduced through the working cannula. It is slowly advanced to within a few millimeters of the anterior cortex of the vertebral body. Caution should be taken not to advance too quickly, as the bone can be quite soft. Notably, performing a biopsy can obviate the need for drilling, as an adequate path for the balloon tamp may have already been created.

The twist drill is removed and the balloon tamp is inserted through the cannula (Fig. 7.7). Different balloon sizes can be used. For most upper and middle thoracic vertebrae, a 10-mm balloon can be safely used. For larger thoracic and lumbar vertebrae, a 15-mm balloon may suffice. The balloon tamp is advanced until the two radiopaque markers, denoting its most distal and proximal ends, have passed beyond the cannula tip. An ideal starting point for the balloon prior to inflation is within

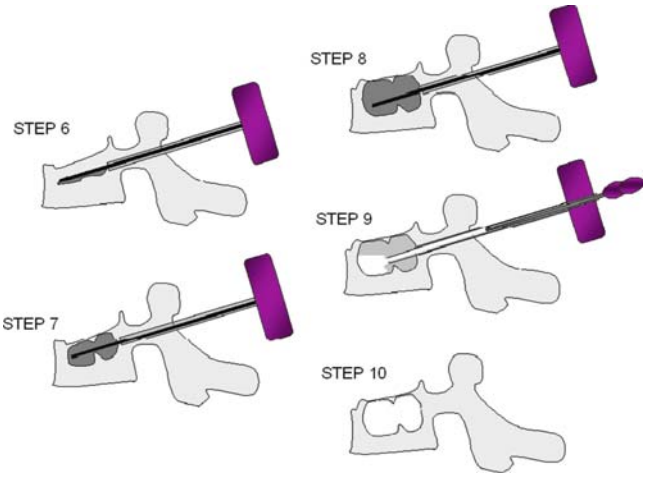

Fig. 7.7 (**Steps 6–10**) After the drill bit is removed, the deflated balloon tamp is inserted through the working cannula (**Step 6**). It is then sequentially inflated using frequent fluoroscopic imaging to monitor the path of the balloon expansion. Ideally, it should flatten against the depressed endplate (**Step 7**). Further inflation of the balloon can elevate the compressed endplate to optimize the fracture reduction (**Step 8**). The balloons are then deflated and removed. Once the cement is of a toothpaste-like consistency, it is carefully inserted into the vertebral body, making sure that it fills the cavity from anterior to posterior (**Step 9**). Once the void is filled, the cement is allowed to harden and the working cannulas are removed (**Step 10**)

the mid-aspect of the vertebral body. The tamp is inflated to an initial pressure of 50 psi until the contralateral balloon is in position. The balloon tamp's central guidewire is removed.

When the second tamp is in position, the balloons are sequentially inflated while the pressure and volume are monitored. While the balloon itself is largely radiolucent, it is inflated with a contrast dye so that it can be fluoroscopically monitored. Care should be taken to avoid breaking through the vertebral body margins. Most commonly this occurs at the endplates. The endpoints of balloon inflation are (1) adequate fracture reduction, (2) pressure of 400 psi, or (3) cortical breach. Frequent images should be taken to monitor the balloon expansion.

Stabilizing the Void: Cement Delivery

Keeping the balloons inflated and in position, the cement mixture is prepared. In a liquid state, the cement is drawn into several 1.5-cc bone filler devices (BFD). These fit snugly into the working cannula to avoid backflow of the cement during insertion. The cement is ready for placement once it has achieved a more viscous state, much like the consistency of toothpaste.

The balloon tamps are deflated and removed. The BFDs are used to insert the cement under lateral, and occasional AP, fluoroscopy. A stylet is used to gently push the cement out of the BFD until the bone void is filled. All steps at this point are followed fluoroscopically. The endpoints of cement insertion are (1) cement has filled the vertebral body, (2) cement begins leaking through the vertebral body, or (3) cement starts to fill the posterior aspect of the vertebral body and approaches the pedicle. In general, the same volume of cement can be used as is noted when the balloon tamp is filled before extraction.

Cement can leak outside the vertebra if the cement is too fluid. If this occurs, the injection can be temporarily stopped, allowing the peripheral cement to begin to cure and "plug the hole." Cement insertion can be resumed slowly, paying close attention to the region of cement extrusion. Fortunately, most cases of cement extrusion are clinically inconsequential.

In most cases, one or two BFDs are used for each side of the vertebra. More cement may be placed if large bone voids with substantial correction of height loss had been achieved with balloon inflation. Cement should be allowed to cure for 5–10 minutes. The rate of cement hardening is affected by mixture proportions, room temperature, and manufacturer. Once the cement has hardened, the cannula and BFDs are removed. Final radiographs are obtained to document the cement placement, fracture reduction, and restoration of alignment.

Postoperative Care

Kyphoplasty can be performed either as a same-day procedure or a short-stay (one- to two-day) admission depending on the patient's medical condition and response to anesthesia, if general was used. Blood loss is miniscule and pain relief often apparent within 24–48 hours. NSAIDs, aspirin, and other agents that may alter the coagulation cascade are avoided until five days after surgery. Bracing is not necessary. Activity restriction consists of avoidance of heavy lifting for about three to four weeks. Activity (walking, sitting, etc.) can begin as soon as the patient is ready.

Complications

The complication rate following kyphoplasty is low. In one study, clinically significant complications occurred in 1.2% of patients and 0.7% of fractures [13]. Cement extrusion can occur in up to 9% of fractures [6]. Fortunately, these are rarely associated with clinical sequelae (Fig. 7.8).

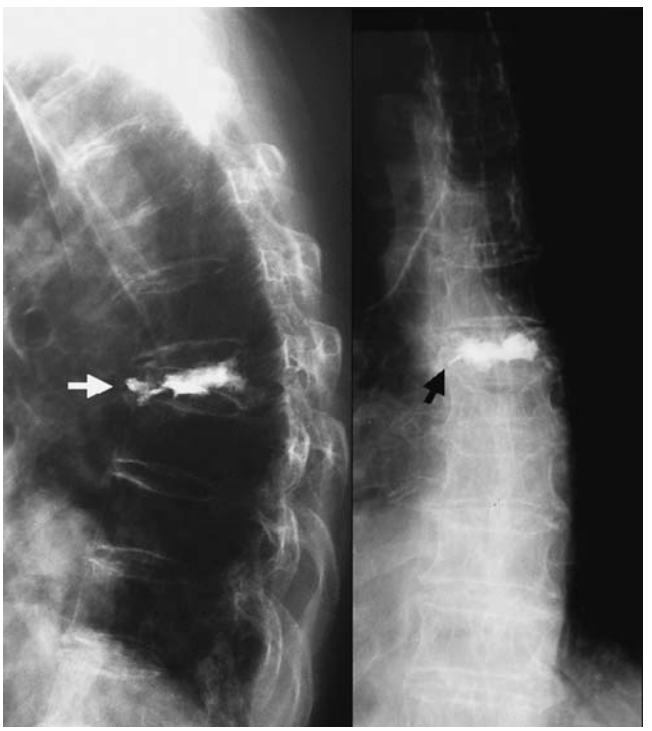

Fig. 7.8 Postoperative lateral and AP radiographs of a patient who had undergone kyphoplasty. Note the small amount of anterior (*white arrow*) and lateral (*black arrow*) cement extrusion. The patient exhibited no clinical sequelae from the extravasation

Neurologic deficit following kyphoplasty is exceedingly rare [3, 6, 14]. In Garfin et al.'s early series [4], two cases were noted. One patient developed partial paraplegia resulting from cement extrusion into the spinal canal. This was the result of improperly placed instruments. The other patient sustained a fracture at the junction of the pedicle and vertebral body during an extrapedicular approach. Subsequently, this patient developed an anterior cord syndrome [3]. In a smaller clinical series by Lieberman et al. [6], no major neurologic injuries were noted. More recent studies, reflecting longer experience with the technique, have not reported significant neurological sequelae [6, 12, 15].

The most common complication with kyphoplasty is transient, self-limiting pyrexia. It is thought to be a reaction to the polymethylmethacrylate (PMMA) [16]. Other reported complications include rib fractures from positioning and intraoperative hypotension from unreacted cement monomer. Epidural hematomata are rare causes of neurological deficit. Pharmacological anticoagulation should not be started until four days after surgery [17, 18].

Pearls and Pitfalls

Difficult Reductions: Using the Bone Curette

In some cases, the balloon tamp does not inflate adequately. Most often this occurs in older fractures that have begun to consolidate. In order to achieve maximal fracture reduction and bone void creation, a specially designed curette can be introduced through the working cannula. Once in position, a thumb-wheel is used to lever a small arm at the end of the tool to create a 90° bend. This can be retracted and advanced to score the bone in the region. The curette is removed, and balloon tamp inflation is again attempted.

Directing Reduction: Use of Directional Balloon Tamps

Standard balloons follow the path of least resistance during inflation. This can lead to eccentric expansion of the tamp, which may risk blowout of the vertebral body walls or endplates. In some of these cases, a directional balloon tamp may be desired. These devices are fixed on one side, allowing the expanding side to be directed away from the area in question.

Vertebral Body Breakthrough: Eggshell Technique of Containing Bone Cement

Cortical violation of the balloon tamp is an inevitable occurrence if one performs enough kyphoplasty procedures. This creates an area through which cement can extrude. If this occurs during cement insertion, the BFD can be removed and the balloon reinserted. The tamp is then slowly inflated to approximate and occlude the hole with the intention that the cement will be evenly dispersed around the balloon. The cement is allowed to slightly cure and the balloon removed, leaving an eggshell-like border of hardened cement. More cement can then be prepared and used to fill the remainder of the bone void.

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Thoracoscopic Deformity Correction

8

Peter O. Newton and Andrew Perry

Introduction

During the last century, the technological advances in the field of spinal surgery had a dramatic impact on the treatment of spinal deformity in children and adults. Before the advent of medications and vaccines, incapacitating spinal deformity was almost inevitable in those who succumbed to tuberculosis and poliomyelitis. In the early 1900s, Lange began to address this problem mechanically by using foreign materials to stabilize the spine internally. In the 1950s and 1960s, owing to the efforts of Harrington and others, the process evolved to create the first generation of modern spinal instrumentation. The Harrington rods were able to correct spinal deformities primarily through distraction. Some of the shortcomings of Harrington rods were addressed in the 1970s by Luque, who used segmental fixation involving sublaminar wires. Anterior approaches and instrumentation-related techniques developed by Zielke as well as Dywer in the late 1960s and mid-1970s allowed for better correction of deformity, with immobilization of fewer motion segments compared with posterior surgery. Multisegmental posterior fixation of the spine was popularized by Cotrel and Dubousset in the 1980s. Finally, in the mid-1990s, video-assisted thoracoscopic techniques (VATS) were developed and are currently in use as a means of performing minimally invasive scoliosis correction.

Indications

Thoracoscopic techniques were initially developed for release and fusion for scoliosis and/or kyphosis of the thoracic spine. Over the last decade, their use has been combined with anterior spinal instrumentation to correct scoliosis and other adult and pediatric deformities. Thoracoscopic spinal instrumentation compares favorably with posterior fusion in terms of coronal plane curve correction and balance, sagittal contour, rate of complications, pulmonary function, and patient-based outcomes. The advantages of the procedure include the need for fewer levels of spinal fusion, less operative blood loss, lower transfusion requirements, and improved cosmesis [1–10]. However, the operative time for VATS procedures can be nearly twice as that for the posterior approach, and the learning curve for thoracoscopy can be substantial [11].

The patient who has an operative indication for an anterior release and fusion is a candidate for a VATS procedure. The three main indications include scoliosis, kyphosis, and congenital deformity. The thoracoscopic approach is appropriate for release and fusion between the T4-T12 vertebral levels in patients with spinal deformity. As additional experience is gained, the procedure may be extended both proximally to T2 and distally to L1.

Scoliosis

In patients with scoliosis, anterior release and fusion is generally indicated for fairly large ($\geq 75^{\circ}$) and/or rigid ($\geq 50^{\circ}$ of residual curvature on side bending) curves that require anterior release and fusion for optimal coronal and sagittal plane correction. The degree to which flexibility can be increased is dependent on the complete removal of the anterior longitudinal ligament, annulus fibrosis, and disc material. In this scenario, the anterior release obtained with a VATS procedure serves to mobilize individual spinal segment and allows for greater coronal and sagittal plane correction than would be obtained with posterior implant systems alone [12–14]. In the most severe cases of scoliosis, resection of the rib head and/or the costovertebral joint may also be required to optimize mobility.

P.O. Newton (✉)
Department of Orthopaedics, Rady Children's Hospital, University of California-San Diego, San Diego, CA 92123, USA
e-mail: pnewton@chsd.org

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Crankshaft Deformity Prevention

Another situation that may require an anterior release and fusion procedure is the prevention of crankshaft deformity. This may occur in patients following an isolated posterior instrumentation who have not yet reached their peak growth rate and are still skeletally immature. In most patients, a skeletal age of 10 years or younger suggests a high probability of development of this deformity. The status of the triradiate cartilage may be a reasonable marker to identify patients who would benefit from an anterior procedure. In skeletally immature children (open triradiate cartilage and Risser 0) with idiopathic scoliosis, the addition of anterior spinal fusion to posterior instrumentation and fusion is helpful in preventing the crankshaft phenomenon [15, 16].

Thoracic Hyperkyphosis Deformities

Another application for VATS is in the correction of adolescent scoliosis patients with associated hyperkyphosis deformity. In Scheuermann's kyphosis, if the thoracic deformity is large ($>80^{\circ}$) and stiff, an anterior release and fusion prior to correction with posterior instrumentation and fusion is an option. Because the risk of pseudoarthrosis is higher in patients with significant kyphosis than scoliosis, it is important to perform a thorough anterior discectomy to increase the area for fusion [17]. With the recent advent of powerful segmental pedicle screw instrumentation, there has been debate regarding the necessity of anterior release prior to the posterior fusion. A recent study comparing traditional anterior/posterior fusion to posterior-only surgery for adolescent hyperkyphosis reported no additional improvement in radiographic outcome with the former [18]. Preliminary anterior release and fusion is less critical when correcting this deformity with a posterior column-shortening procedure and pedicle screw instrumentation.

Other, more challenging applications of VATS for kyphotic deformities include congenital kyphosis, kyphosis associated with neuromuscular diseases and neurofibromatosis, and postlaminectomy states. These deformities should be reserved for the accomplished VATS surgeon who has mastered simpler techniques. In these deformities, the need for a thorough discectomy and obtaining a solid fusion is even more critical for long-term success despite the addition of posterior instrumentation and fusion.

Congenital Deformity

The majority of patients undergoing treatment for congenital deformities of the spine are less than 5 years of age and may also require anterior release and fusion over several levels. Since the technical challenges of thoracoscopy increase as the size of the child decreases, endoscopic procedures can be difficult in this segment of the pediatric population. Endoscopic techniques can be applied to these patients in an identical manner as for idiopathic scoliosis patients to perform the anterior portion of a circumferential fusion. An anterior hemiepiphysiodesis as well as excision of lower thoracic-level hemivertebrae may be performed thoracoscopically in these patients.

Contraindications

Thoracoscopic procedures require adequate working space in the chest cavity in order to manipulate both the endoscope and instruments. This generally requires collapse of the ipsilateral lung on the side being operated on. The pulmonary status of the patient must therefore allow single-lung ventilation. Pleural adhesions between the lung and the chest wall can limit the ability to deflate this organ. Although minor adhesions can be divided, extensive areas of adhesions between the chest and lung can make adequate lung collapse extremely challenging. Previous rib cage disruption or pulmonary infection, which may have resulted in intrathoracic pleural adhesion formation, should be considered relative contraindications. In patients with severe pulmonary insufficiency and poor preoperative pulmonary function, from whatever cause, VATS is contraindicated.

In patients with severe curves (>100–120°) in which the spine has become closely approximated to the rib cage, the field of vision and the maneuverability of the working instruments can be compromised. Preoperatively, a working distance of 2–3 cm on radiographs should be considered the minimum before attempting a VATS procedure.

Achieving single-lung ventilation and obtaining adequate working space in children weighing less than 30 kg can also be challenging [19]. Although children weighing less than 30 kg have been safely treated with the anterior thoracoscopic approach, the relative benefit of this minimally invasive technique seems to be reduced in very small patients. For very small patients (under 20 kg), thoracoscopic surgery should remain a relative contraindication, especially during a surgeon's learning curve [19]. In larger patients, visualization is often limited by excessive bleeding or inconsistent lung deflation. At any point during the endoscopic procedure, conversion to an open approach must be considered if visualization is inadequate.

Thoracoscopic Technique

The VATS team should include an anesthesiologist capable of performing one-lung anesthesia using a flexible bronchoscope, a bronchial blocker, and/or double-lumen tube. The spine surgeon or a general/thoracic surgeon experienced in thoracotomy techniques should be available in case conversion to an open procedure becomes necessary. The general principles of the thoracoscopy technique are highlighted in the following text.

Preoperative Planning

Proper patient selection is critical to the success of thoracoscopic spinal deformity correction. Patient lung function must be assessed with specific attention to asthma, severe restrictive or other cardiopulmonary diseases. Patients must also be counseled on the possibility of conversion to an open procedure should the need arise.

Surgical Equipment

Thoracoscopic surgery requires high-quality endoscopes and a three-chip video system to ensure good visualization. Adequate intraoperative visualization requires endoscopes with angled viewing (0–45°). Other equipment includes endoscopic lung retractors, peanut dissectors, a suction/irrigation device, a harmonic scalpel, rongeurs, curettes, and modified mechanical endplate shavers. In addition, a bone mill for morselizing bone is helpful if autogenous bone grafting will be performed. Somatosensory and motor evoked potential monitoring in the upper and lower extremities can also be valuable.

Positioning of the Patient

The patient is positioned on a radiolucent table in the lateral position with an axillary roll in place. The legs are scissored to prevent excessive pressure on the down-side leg. The lateral position allows for anterior placement of ports on the chest wall, which enables greater circumferential visualization and access to the vertebral bodies and discs. The surgeon and assistant stand anterior to the patient while the video display monitor is placed behind the patient. This helps with spatial orientation of the operative field and allows for a better "mind's-eye view" of the procedure. At the head of the table on either side of the anesthetist, the harmonic scalpel generator, electrocautery generator, suction/irrigation, and cell saver are positioned.

Port Location

The number of ports and their location are dictated mainly by the deformity and the number of levels that require surgery. Generally, four ports along the anterior axillary line are usually sufficient for a six- to eight-level release and fusion [Fig. 8.1(a)]. Port spacing is also dependent on the working distance from the chest wall to the spine and on angulations of the endoscopic viewing optics. The higher the viewing angles of the endoscope, the greater the possible spacing of the ports while maintaining an inline view of the disc space. Typically, the instrument for discectomy is placed in the port that is parallel to the discs, and the endoscope is placed either one port proximal or one port distal to this level. Port placement along the anterior axillary line optimizes the exposure and visualization of the anterior spine and affords both a larger field of view with the scope and an increased working distance for the instruments.

For anterior instrumentation, three ports along the posterior axillary line are used together with two ports on the anterior axillary line. Proper placement of the thoracoscopic portals is crucial and is aided by use of the image intensifier. With the patient in the direct lateral position on the operating table, the image intensifier is used to mark a longitudinal line on the patient corresponding to the sagittal alignment of the spine [Fig. 8.1(b)]. For procedures that require instrumentation, the midlateral position of the vertebra to be instrumented is marked on the lateral chest wall and usually approximates the posterior axillary line. With the image intensifier in the anteroposterior plane, the orientation of each vertebra to be instrumented in the frontal plane is also marked on the posterior aspect of the patient [Fig. 8.1(b)]. The intersection of a line marking the frontal plane orientation and the midlateral portion of that vertebral body demarcates the ideal chest wall entry site for an appropriate screw trajectory.

Skin incisions (1.5 cm in length) are made, and with blunt dissection through the musculature, the chest cavity is entered with Mayo scissors. Rigid tubular ports are placed between the ribs along the anterior axillary line. Care should be taken in placing the portals, particularly when placing them distally, to avoid penetrating the diaphragm. Retraction of the lung allows visualization of the spine (Fig. 8.2).

Spine Exposure

Exposure of the spine requires a longitudinal incision of the pleura approximately 5 mm anterior to the rib heads followed by retraction of the pleura and segmental vessels off its anterior aspect. Coagulation of these vessels with a

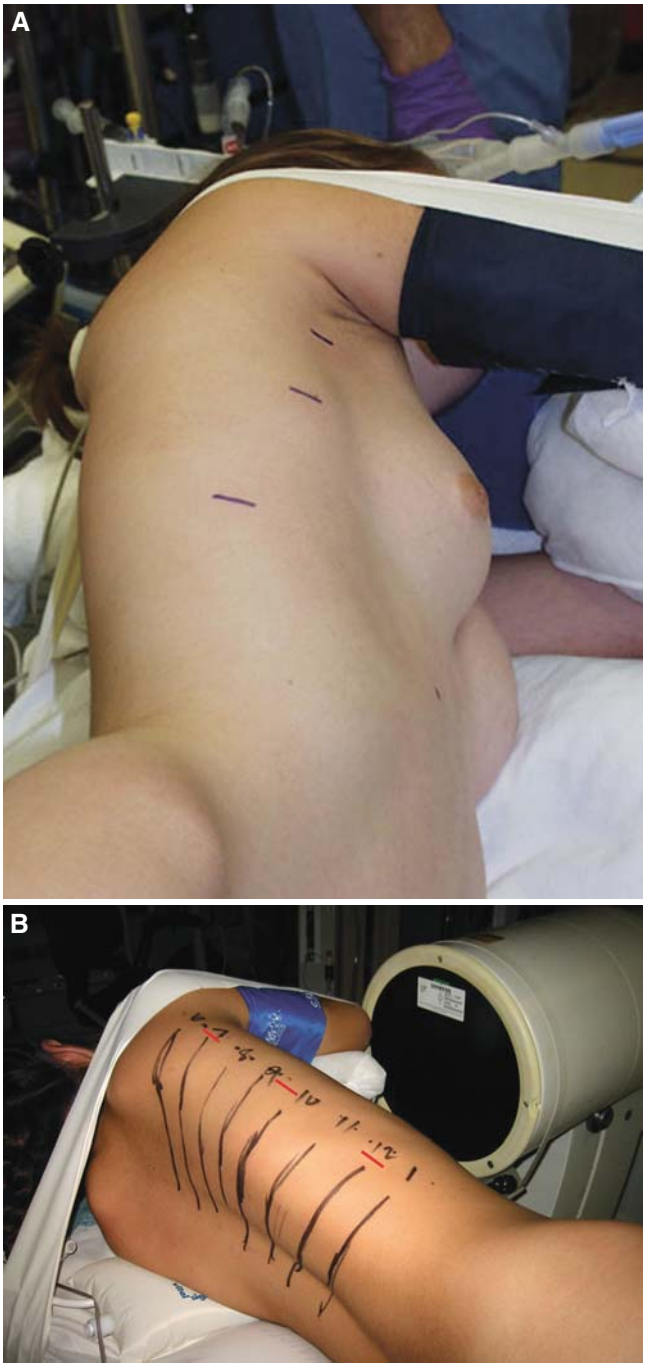

Fig. 8.1 (**a**) On the table, surface markings for planned placement of anterior ports for thoracoscopic release procedure. (**b**) The planned positions for the posterior ports utilized for placing anterior vertebral body screws thoracoscopically would be positioned directly lateral over T7, between T9 and T10, and over T12 in this case, planning for instrumentation between T6 and T11

harmonic scalpel before division allows excellent hemostasis during circumferential exposure (Fig. 8.3). Once the loose areolar tissue has been divided, the azygos vein, esophagus, and aorta are reflected anteriorly off the spine, and sponges are packed between the anterior

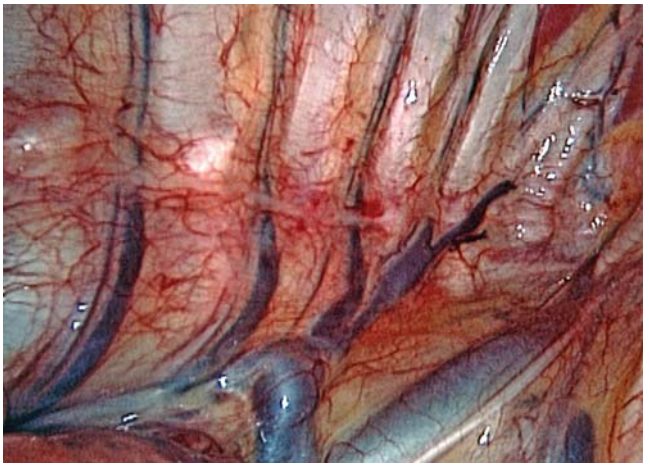

Fig. 8.2 Proximal aspect of the spine with the lung retracted

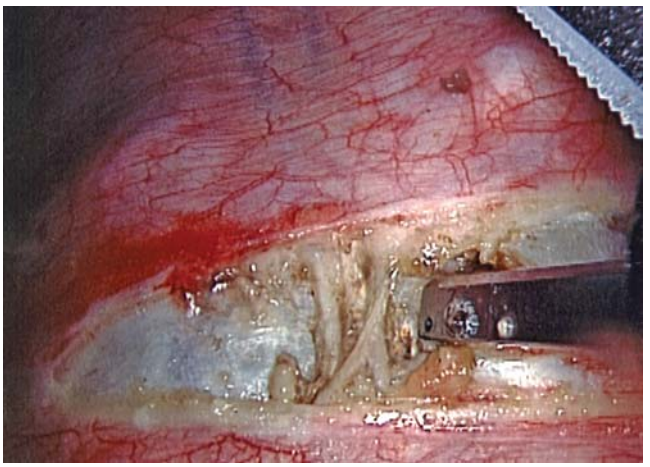

Fig. 8.3 The segmental vessels coagulated prior to division with the harmonic scalpel. Division of these vessels allows wide exposure of the concave side of the spine

longitudinal ligament and the pleura. This provides protection to these structures during further surgical maneuvers and also improves the circumferential visualization of the discs (Fig. 8.4). Surgical procedures that extend to the T12-L1 disc space require division of the diaphragm insertion. This can be accomplished by extending the longitudinal incision of the pleura onto the inferiorly retracted diaphragm and by blunt stripping of the diaphragm from the anterior aspect of the spine.

Anterior Release

An endoscopic anterior release may be performed in conjunction with anterior instrumentation for curve correction, or prior to posterior instrumentation as either a combined or staged procedure. Using the harmonic

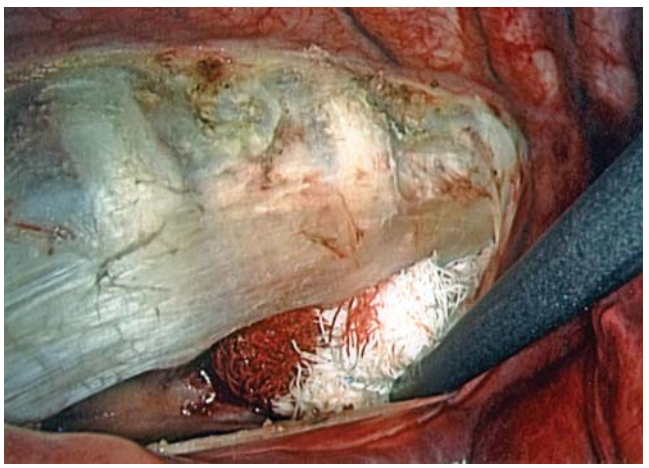

Fig. 8.4 Packing sponges being used to retract the great vessels and expose the anterior circumference of the spine

scalpel, disc excision is initiated with incision of the annulus and anterior longitudinal ligament. For the patient with a typical right-sided idiopathic curve, an up-biting rongeur is first used to remove the most anterior and concave aspect of the annulus of the disc [Fig. 8.5(a)]. It is important not to remove excessive bone, which may result in heavy bleeding and will interfere with visualization. The discectomy then moves toward the convex side to the level of the rib head. The deep aspects of the disc should only be removed under direct visualization [Fig. 8.5(b)]. To prevent injury to the neural elements, the posterior longitudinal ligament should not be breached. An angled curette or rongeur is useful in removing the endplate cartilage. Once this is excised, hemostasis can be aided by immediate cancellous bone grafting or by placement of hemostatic agents such as Surgicel (Ethicon, Somerville, NJ). The endoscopic retractor and working instruments are varied from port to port to maintain ideal visualization and access to the different levels of the spine.

To increase the likelihood of a solid fusion, each evacuated disc space can be filled with bone graft. This may be autologous from the patient's ribs or ileum, allogenic (freeze-dried or frozen), or artificial bone graft substitute. The morsellized graft can be delivered through a tubular plunger device into each evacuated disc space.

Anterior Instrumentation

The insertion of vertebral body screws requires the use of at least three of the planned posterior axillary line ports. However, before making a skin incision, the port location can be confirmed by placing a K-wire through the chest wall at each proposed site. With the aid of fluoroscopy, anteroposterior views of the spine are obtained to ensure proper orientation of the K-wire with the vertebrae. A rigid 15-mm thoracoport is used to place instrumentation.

The starting point for the screw is in the mid- to superior aspect of the vertebral body just anterior to where the rib head articulates. An awl is used to initiate the hole, followed by a tap. The screw path is tapped through the far cortex; using a ball-tipped calibrated probe, the exact length of the screw is determined. Screws are available in 2.5-mm increments to accommodate the variety of vertebral body dimensions. Visualizing directly through the anterior and posterior portals as well as with the endoscope and image intensifier ensures proper screw placement. Subsequent screws are placed in a similar fashion moving the portal one rib space distally. Care should be taken to appropriately align each screw to make later rod insertion as straightforward as possible (Fig. 8.6). Each of the screws should be placed with a bicortical purchase. However, given the location of the aorta on the left side of the vertebral bodies, excessive screw penetration should be avoided. Typically, two or three screws can be placed through each skin incision.

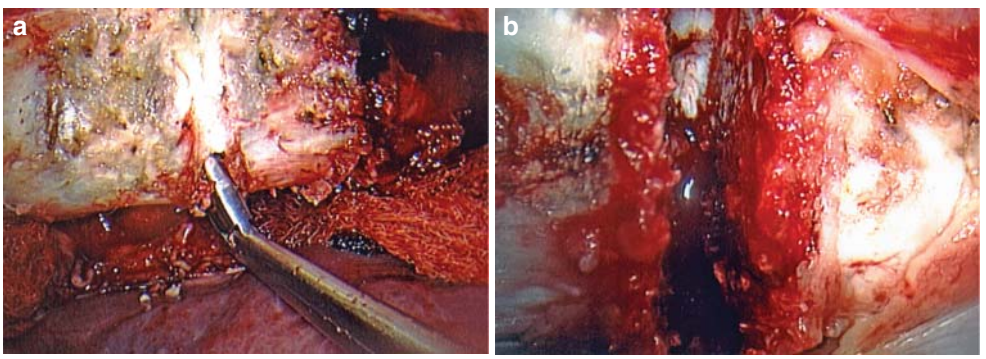

Fig. 8.5 (**a**) Discectomy is initiated at the most anterior and concave aspect of the disc with an up-biting rongeur. (**b**) Deep excision of the disc is followed by removal of endplate cartilage from the superior and inferior aspects of the vertebral body

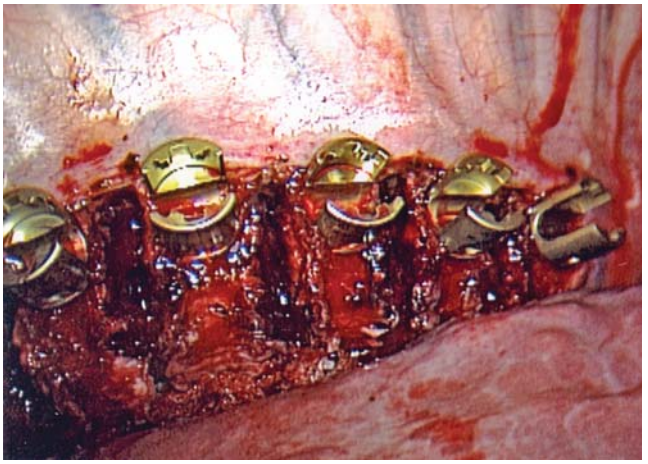

Fig. 8.6 Vertebral body screw insertion. Appropriate screw alignment is required to facilitate rod insertion and ensure deformity correction

A malleable calibrated template is inserted through the distal port to determine the rod length. The rod is contoured to the desired shape anticipating a 1- to 1.5-cm shortening of the spine due to compression. A hex-end holder is then used to maintain the orientation of the contoured rod while it is being placed onto the head of the vertebral body screws (Fig. 8.7).

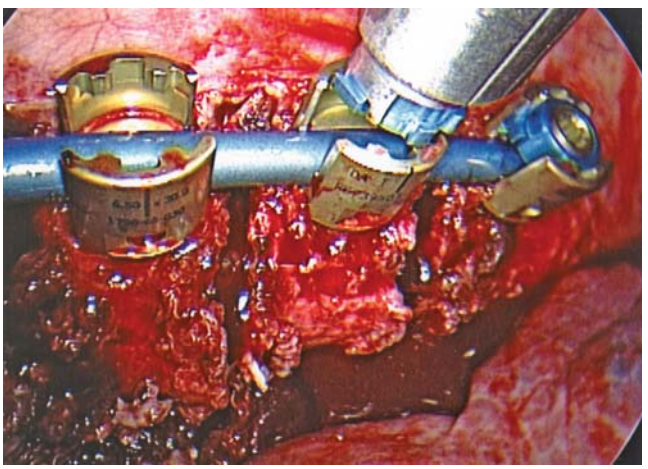

Fig. 8.7 The rod is sequentially engaged beginning with the proximal screw

As each screw cap is captured on the rod, morsellized autogenous bone graft is added prior to compression of the construct. An interbody device or cortical allograft is used at the more distal levels where the interspace may require structural support to maintain sagittal alignment. Compression is achieved with an endoscopic compressor (Fig. 8.8). Deformity correction is accomplished by cantilevering a rod into position, beginning by engaging the proximal screws first. This combination of rod cantilevering, facilitated with

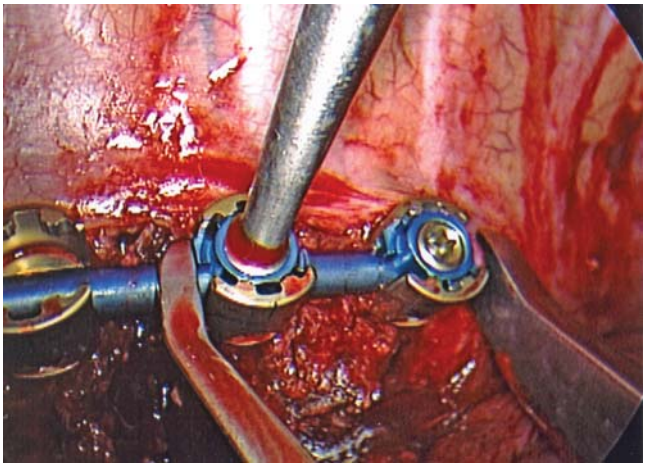

Fig. 8.8 As each screw is captured, bone grafting and compression are performed with an endoscopic compressor

an approximating device, and segmental vertebral body compression provides coronal plane correction of the scoliosis, sagittal restoration of kyphosis, and axial plane derotation of the spine (Fig. 8.9).

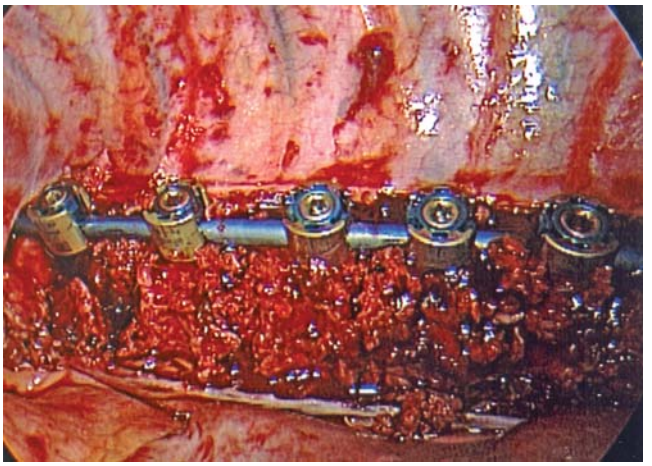

Fig. 8.9 Entire construct with morsellized bone graft in place between each vertebra

Pleural Closure

Pleural closure is accomplished with an endoscopic stitching device (Figs. 8.10 and 8.11). The advantages of the pleural closure are debated, but this may limit bleeding, maintain the bone graft in position, and decrease pleural scarring. A chest tube is inserted through an inferior portal after removal of debris and irrigation of the ipsilateral hemithorax. Lung reinflation is confirmed, and bronchial suctioning of the dependent lung is done to reduce the likelihood of developing postoperative atelectasis.

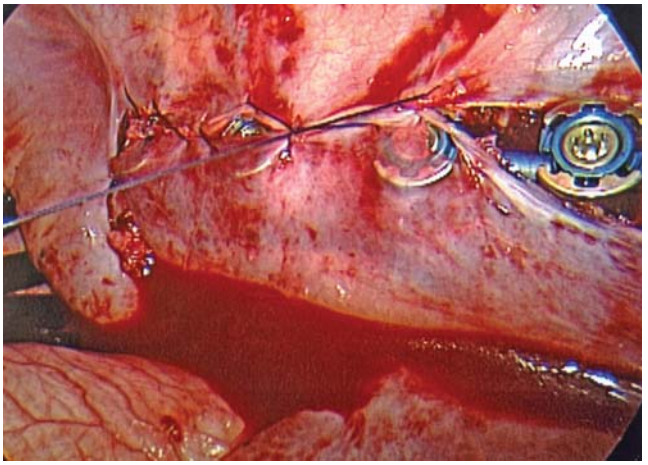

Fig. 8.10 An EndoStitch device is used to reapproximate the pleura

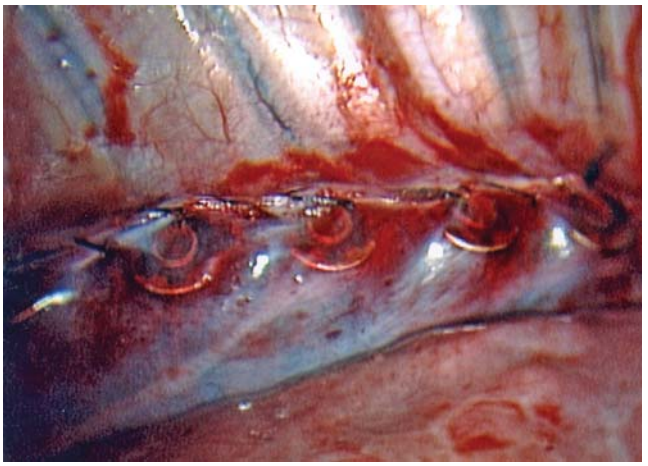

Fig. 8.11 Following closure of the pleura, irrigation of the chest cavity is performed

Postoperative Management

Patients who have undergone thoracoscopic surgery have a slightly shorter time to discharge and generally recover more completely than those who had the open thoracotomy procedure [3, 4, 20–22]. The chest tube is removed when the output slows to 50–75 ml per 8-h period, which usually correlates to day 3–4 postoperatively. Once the chest tube has been removed, a postoperative thoracolumbosacral orthoses (TLSO) is prescribed for three months (worn when the patient is out of bed) if a single anterior rod system was utilized. Posterior instrumentation cases generally do not require postoperative external immobilization.

Complications

The complications of thoracoscopic release and fusion are essentially the same as those of open anterior spinal surgery. Intraoperatively, complications that may occur include injury to the heart, great vessels, lung, diaphragm, spinal cord, or thoracic duct. However, with the endoscopic approach, these complications may be more challenging to deal with.

The greatest likelihood for iatrogenic injuries occurs when visualization is suboptimal. As such, maintaining adequate visualization is the most important aspect of the procedure. The most common hindrance to visualization is excessive bleeding, which can come from the segmental vessels during spinal exposure, from epidural veins, or from exposed bone. Each source of bleeding must be minimized, as much as possible, with the appropriate use of electrocautery, ultrasonic coagulation, bone waxing, and early disc space bone grafting.

The likelihood of lung injury occurs when there is inadequate deflation or retraction of the structure. A lung that has significant pleural adhesions is at risk of injury during placement of the initial thoracoscopic portal. Directing sighting down the portal from outside to inside the chest is one way to ensure that no lung tissue is in the path of the instruments. After a portal has been established, an endoscope can also be used to confirm that a clear path exists from the portal to the spine. Great care must also be taken during advancement of guidewires to reduce the likelihood of damage to vital structures, including the contralateral lung [23].

Injury to the thoracic duct that is recognized during surgery by the presence of cloudy fluid may be repaired by sutures or clips. If a chylous effusion develops postoperatively, a nonfat diet and/or thoracic duct ligation may help [24, 25].

Spinal cord injury during thoracoscopic release and fusion surgery may result from either direct trauma during disc excision or vascular insufficiency secondary to segmental vessel ligation. Appropriate visualization especially into the depth of the disc space can help reduce the occurrence of this complication. An attempt to maintain the segmental vessels during exposure of the spine should be considered in "high-risk" patients. Monitoring of spinal cord function after placing an endoscopic vessel clip may be useful in revision cases, congenital deformity, and kyphosis.

Illustrative Case

A 14-year-old female, who was otherwise healthy, presented with a 50° right thoracic scoliosis (Fig. 8.12). The thoracic kyphosis between T5 and T12 was 13°, and the Lenke

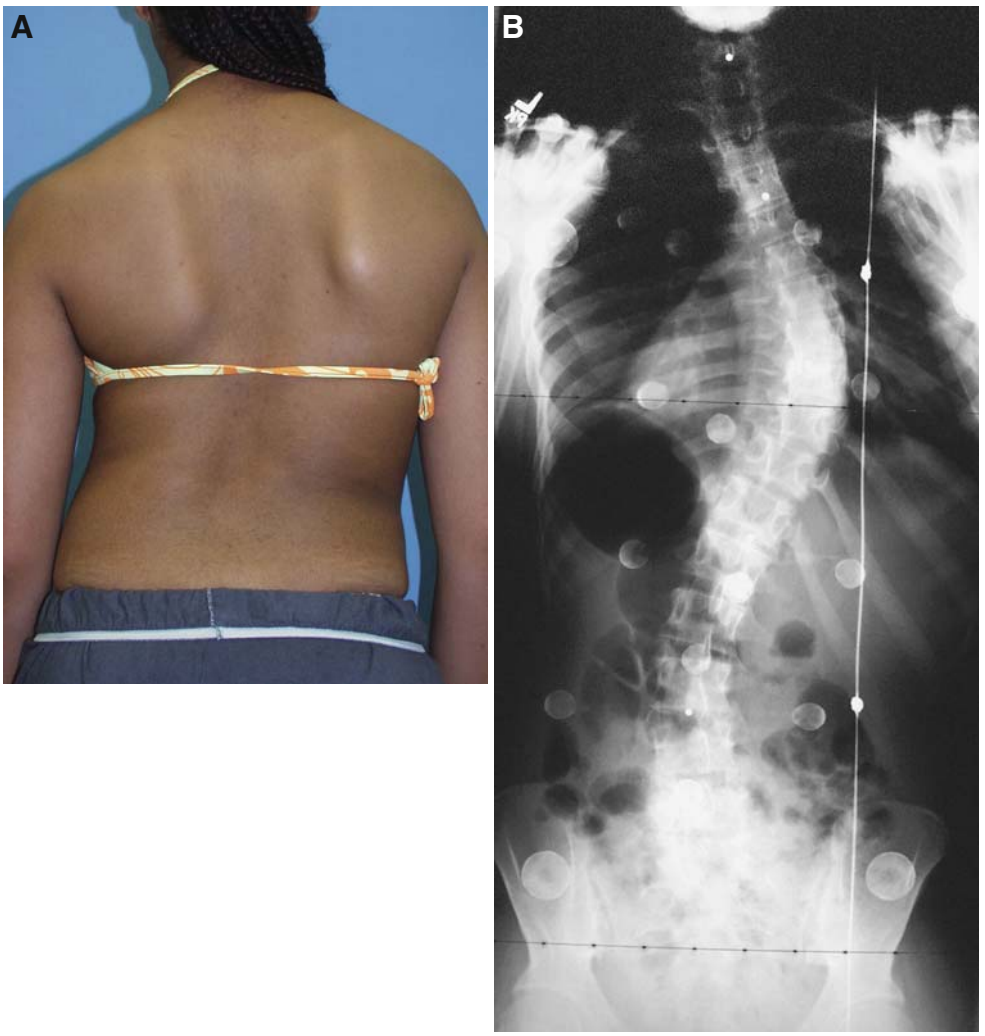

Fig. 8.12 (**a**) Clinical appearance and (**b**) preoperative posteroanterior (PA) radiograph of a 14-year-old female with a 50° Lenke 1A N curve

classification of this curve was considered to be 1A N. The end vertebrae of the thoracic curve were T5 proximally and T12 distally (Fig. 8.12). The patient underwent a thoracoscopic anterior fusion with a titanium single-rod instrumentation placed between T5 and T12. A structural fibular allograft was placed within the T11-T12 disc space. All levels received morsellized iliac crest autograft bone. The operative time was 5 h, with an estimated blood loss of 300 ml. The chest tube was removed on the day of discharge (postoperative day 4). She wore a TLSO for three months postoperatively. Her radiographs and clinical appearance six months postoperatively suggested satisfactory correction and demonstrated radiographic evidence of arthrodesis (Fig. 8.13).

Summary

Over the last decade, thoracoscopic techniques have been combined with anterior spinal instrumentation to correct scoliosis and other adult and pediatric deformities. Thoracoscopic spinal instrumentation compares favorably with posterior fusion in terms of coronal and sagittal plane correction, complications, and patient-based outcomes. The advantages of the procedure include less operative blood loss, lower transfusion requirements, and improved cosmesis. However, the operative time for thoracoscopic procedures can be nearly twice that for the posterior approach, and the procedure is associated with a significant learning curve and the need for sophisticated equipment.

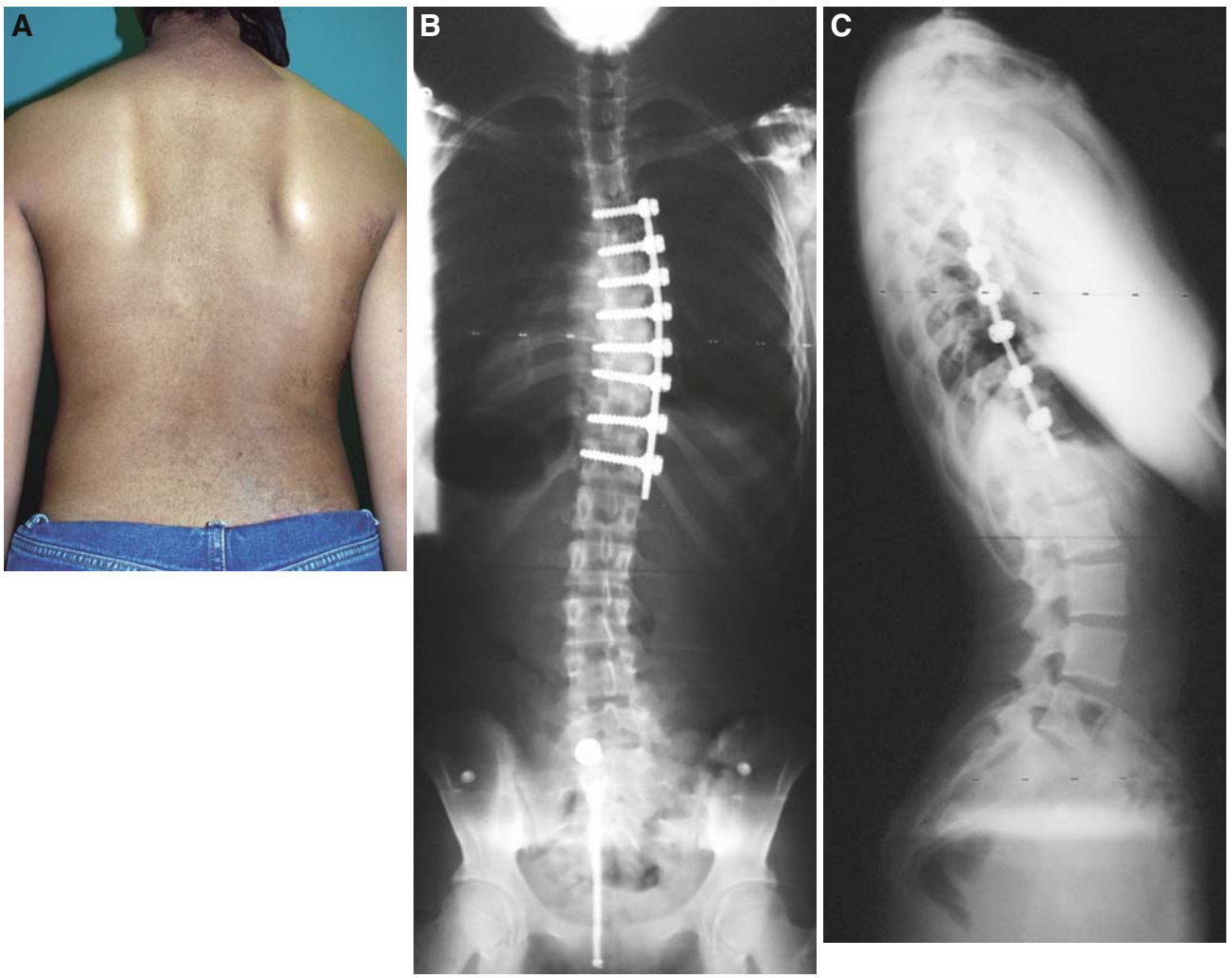

Fig. 8.13 (**a, b**) Postoperative radiographic views and (**c**) and the clinical appearance of the patient six months after the procedure

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Paracoccygeal Transsacral Access to the Lumbosacral Junction for Interbody Fusion and Stabilization

9

Isador H. Lieberman and Andrew Cragg

Introduction

Minimally invasive spinal surgery is not one single device, technique, or tool. It is a philosophy of targeting the pathological tissue while minimizing collateral tissue damage in order to preserve native function and promote rapid recovery. In the development of minimally invasive surgical techniques, one requires a thorough understanding of the spinal anatomy, an appreciation of the pathology, and specialized tools to facilitate the intended intervention.

In the case of anterior lumbosacral interbody fusions, multiple exposure techniques and interbody devices are available to facilitate a fusion. The exposure techniques to the lumbosacral segment have evolved from transperitoneal to retroperitoneal and even laparoscopic approaches. These exposures, however, require mobilization of the abdominal contents and vascular structures, which carries an element of risk and also frequently involves specialized expertise to perform the exposure safely. The use of interbody implants with these exposures necessitates partial resection of the annulus to place the implant. This, in turn, may contribute to a destabilizing effect on the spine despite the use of a specific implant.

In response to the limitations of these contemporary exposures and techniques for lumbosacral fusions, Cragg et al. [1] recently described a novel percutaneous, fluoroscopically guided, access method to the lumbosacral junction. The access is gained through a paracoccygeal incision with blunt dissection through the presacral space, all while the patient is positioned prone. This approach allows for axial transsacral access to the lumbosacral junction. Along with this exposure, specially designed tools to evacuate the disc space, prepare the endplates, and introduce graft material, as well as a specialized axial stabilization rod, have all been developed to facilitate a minimally invasive fusion of the lumbosacral junction.

Presacral Anatomy

The paracoccygeal presacral access to the lumbosacral junction capitalizes on a well-defined anatomic potential space between the anterior surface of the sacrum and posterior surfaces of the sigmoid colon and rectum (Fig. 9.1). This presacral space is bounded by visceral fascia on the sigmoid colon and rectum and by parietal fascia on the anterior surface of the sacrum. The space is filled with areolar tissue and fat. As the rectum and sigmoid colon are not tethered to any structures in the course of the presacral space, they can be easily mobilized with a blunt spatula or dissector. As the sacral nerve roots exit the foramina, they course laterally and inferiorly away from the midline presacral space. Since this space is devoid of any significant vascular or neurological elements, there are no obstacles to establishing a corridor for access.

Yuan et al. [2] studied the anatomic relationships in this space. They reported that at the lumbosacral junction, the

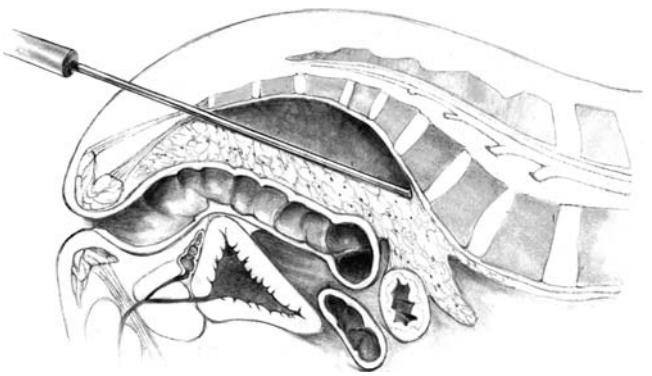

Fig. 9.1 Schematic of the presacral anatomy

I.H. Lieberman (✉)
Medical Interventional and Surgical Spine Center, Cleveland Clinic Florida, Ft. Lauderdale, FL 33331, USA
e-mail: lieberi@ccf.org

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iliac vessels and their accompanying sympathetic hypogastric nerves course laterally over the sacral ala. In the midline just beyond the lumbosacral junction, the midline sacral artery and vein follow a variable course and typically terminate in a fine reticular mesh. They defined the coronal safe zone at the S1-S2 interspace as over 6 cm wide in both males and females on the basis of CT and MRI measurements. Therefore, at the typical docking and entry point into the sacral promontory, which is usually at the S1-S2 junction, there are no significant obstructions.

Parke et al. [3] described the variability of the middle sacral artery in 20 cadavers, reporting that in humans, it is only a minor contributor to any major segmental arteries, through bilateral segmental branches. Furthermore, it was found to be absent in many specimens.

Oto et al. [4] described the sagittal width of the presacral space at the S1, S2, and S3 vertebral levels retrospectively on MRI in 193 patients. They found that in males the presacral width was significantly wider than in females, and in general the presacral space is at least 1 cm wide in over 60% of males and 40% of females.

Evolution of Technique

The paracoccygeal presacral access to the lumbosacral junction was validated in a series of cadaver, animal, and then human trials. Cragg et al. [1], in a series of 15 cadavers, refined the access technique and the necessary instruments. The instruments evolved to include dissectors, cannulas, drills, discectomy tools, bone graft application tools, and axial rod implantation tools. The procedure was validated with a fully percutaneous, fluoroscopic approach through a single 2-cm paracoccygeal incision. Cragg et al. then assessed the safety of the access procedure in a series of six consecutive animals. The access was performed without adverse events. Lumbosacral access in the animals was confirmed fluoroscopically by axial discography. Following the success of the preclinical studies, Gutterman undertook a series of consecutive biopsies of the lumbosacral disc and vertebral body region for suspected pathologic lesions in three patients. Again, the technique posed no significant issues.

Surgical Technique

Preoperative Planning

In preparation for the surgical approach, the radiographic images, including a full sacral view, are analyzed to determine if the anatomy is suitable for the paracoccygeal transsacral approach to the lumbosacral junction. The standard field of view for a lumbar MRI scan should be expanded to include the entire sacrum and coccyx on the sagittal views. With the radiographs and MRI images, one can plan and map the trajectory of the access and subsequent implantation of the axial rod (Fig. 9.2).

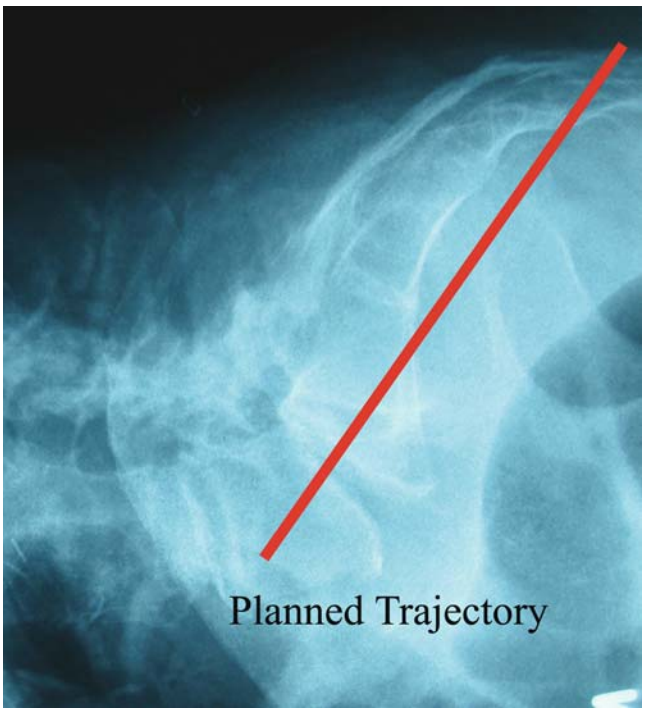

Fig. 9.2 Preoperative planning

Patient Preparation

Typically, a standard bowel preparation the evening before surgery is advisable. In the operating room, the patient is positioned prone onto a radiolucent table with the lumbar spine in extension to facilitate lumbar lordosis. The lumbar and the sacrococcygeal regions are prepped and draped. The operative area should be isolated from the anus with an occlusive dressing (Fig. 9.3).

Operating Room Setup

Once the patient has been positioned, two image intensifiers are positioned for simultaneous biplanar fluoroscopy. The posteroanterior (AP) C-arm should be adjusted to project a lordotic view of the lumbosacral junction. The lateral (Lat) C-arm should be adjusted to achieve a true lateral view of the lumbosacral junction. The lateral and AP C-arms should be draped such that they can move in a parallel fashion from the tip of the coccyx to the lumbosacral junction freely as needed throughout the procedure (Fig. 9.4).

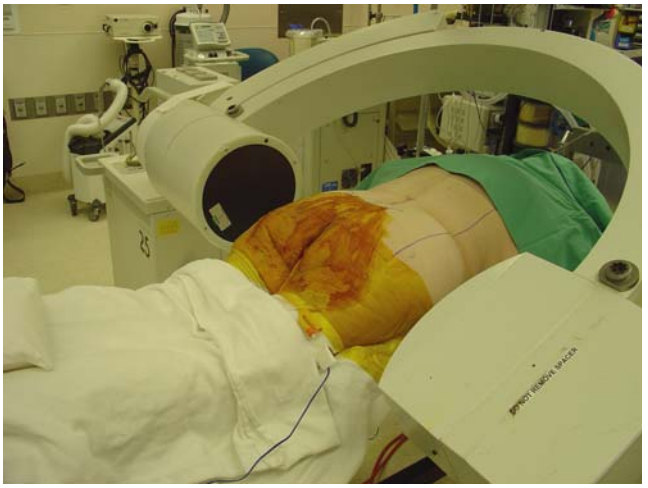

Fig. 9.3 Isolation of surgical site

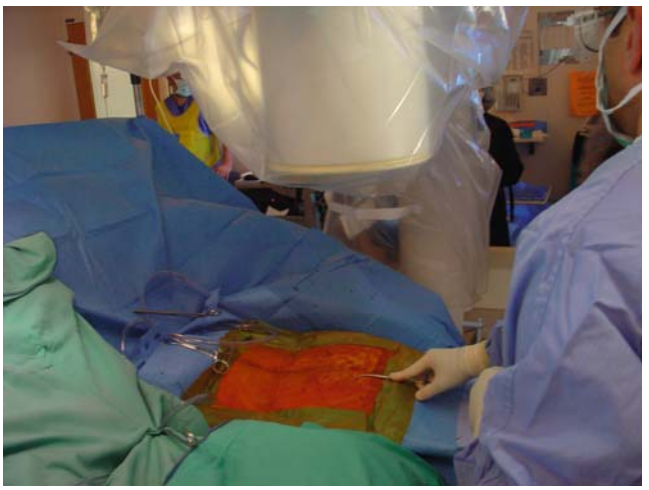

Fig. 9.4 Setup of C-arms to facilitate posteroanterior and lateral images

Access and Trajectory Planning

To begin, palpate the coccyx and sacrotuberous ligament arch, and then create a 15- to 20-mm incision through the skin and superficial fascia 2–3 cm caudal to the paracoccygeal notch and left or right of the coccyx (Fig. 9.5). After making the initial 2-cm paracoccygeal skin incision, use a Kelly clamp to bluntly dissect down to the parietal fascia. Penetrating the fascia is necessary to access the presacral space and the anterior face of the sacrum. Penetrating the fascia can be accomplished using two methods, including finger dissection, blunt guide pin dissection, or a combination of the two. Once achieved, the blunt guide pin is then advanced in a cephalic direction under fluoroscopic guidance in the midline, keeping the tip engaged on the anterior cortex of sacrum to approximately the S1-S2

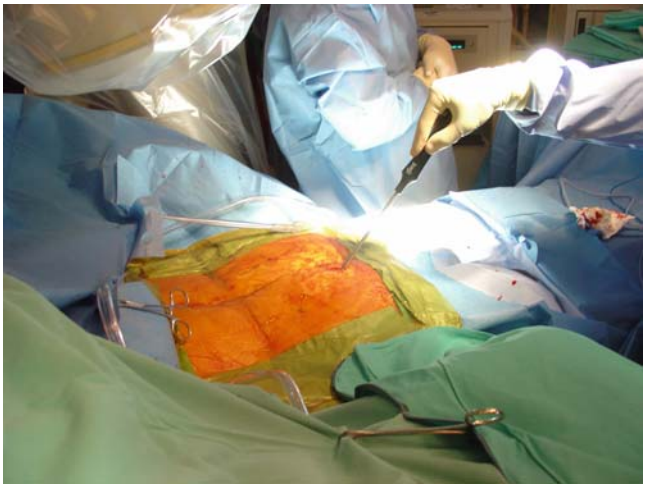

Fig. 9.5 Paracoccygeal 2-cm incision

junction (Fig. 9.6). This maneuver is accomplished with "fingertip" control on the handle of the Guide Pin Introducer and should be completed using fluoroscopic guidance in both the AP and lateral planes.

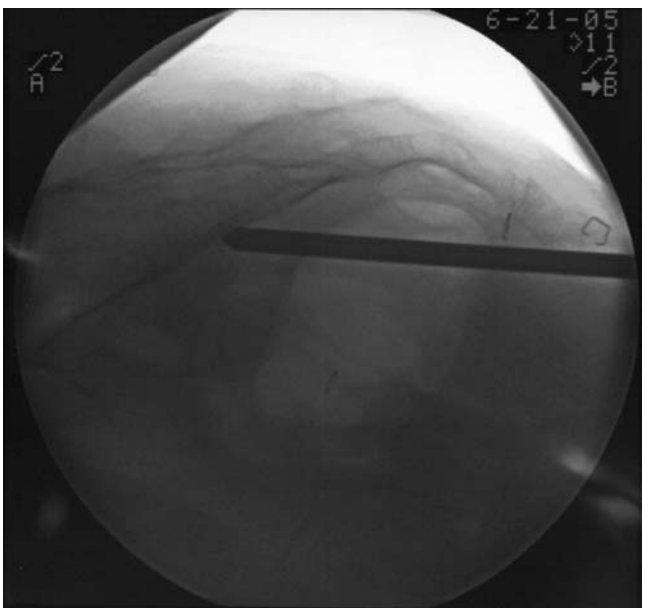

Fig. 9.6 Intraoperative fluoroscopic image of blunt guide pin

Centerline Trajectory

Once the guide pin has reached the S1-S2 junction, a midline trajectory for entry into and through the L5-S1 disc space is established by adjusting the angle of the guide pin. The aim is to traverse the L5-S1 disc space in its midpoint in both the AP and lateral planes. Once the

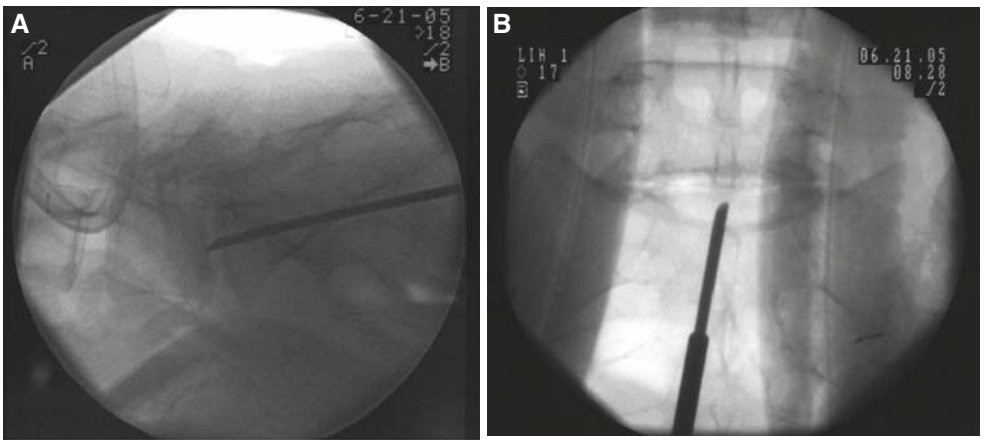

Fig. 9.7 (**a, b**) Intraoperative fluoroscopic image of bevel-tip K-wire across lumbosacral junction

trajectory has been established, an exchange system is used to switch the blunt guide pin for a bevel-tip extended K-wire. The bevel-tip K-wire is then advanced across the disc space, keeping its predetermined trajectory (Fig. 9.7).

Working Cannula and Disc Space Preparation

Once the guidewire has been situated, a series of instruments is used to sequentially dilate the soft tissue and sacral corticocancellous bone to create the working channel and to dock the working cannula (Fig. 9.8). Following this, a series of tools is used to prepare the disc space for fusion. These include specially designed radial cutters and brushes (Fig. 9.9).

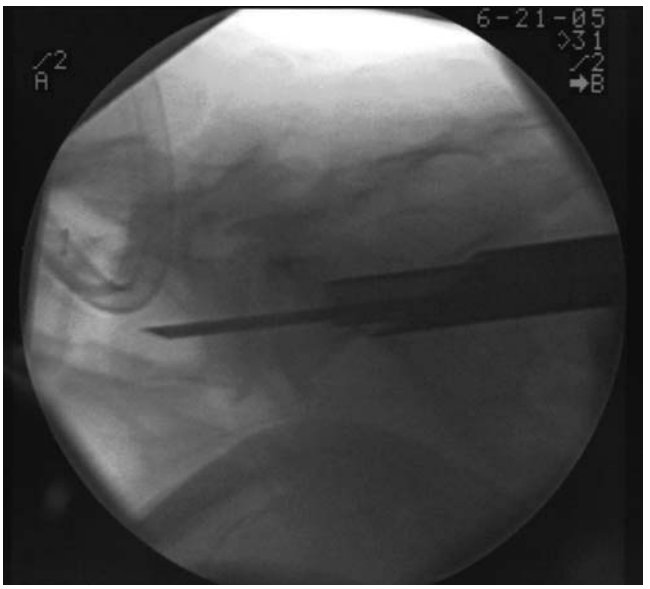

Fig. 9.8 Intraoperative fluoroscopic image of working cannula

Fig. 9.9 Instruments designed to evacuate disc space and prepare endplates for fusion

Bone Graft Application

After the disc space has been evacuated and the endplates have been denuded of cartilage, bone graft material is deposited into the disc space using the bone graft funnel. Approximately 10–15 cm^3 of material is delivered into the disc space.

Preparing to Implant the Axial Rod

At this point, a drill is advanced across the disc space and into the L5 vertebral body to create a channel to accommodate the axial rod. The depth of the drilling is guided with the fluoroscopic views (Fig. 9.10).

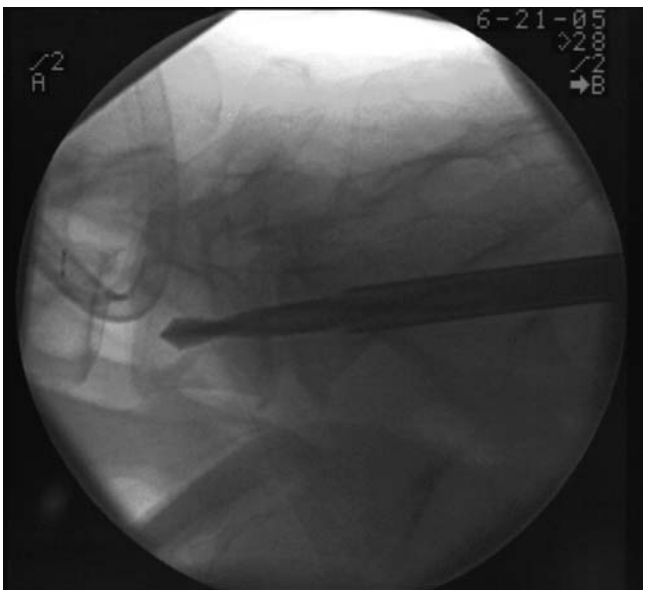

Fig. 9.10 Intraoperative fluoroscopic image of drill across disc space into L5 vertebra

Axial Rod Implantation

The final step involves the implantation of the axial stabilization rod over a guidewire. This frequently involves a significant torque force to advance the axial rod across the sacral promontory, across the disc space, and into the L5 vertebra (Fig. 9.11).

Potential Complications

To date, over 2,000 cases using a paracoccygeal exposure have been performed worldwide (Trans1 Inc., Wilmington, NC, www.trans1inc.com). Experience with this technique is still too recent to accurately comment on the magnitude of risk associated with it and the various potential complications. However, the possible complications that may be encountered as they relate to the surgical access include infection, injury to the presacral structures, fracture of the sacral promontory, and inaccurate trajectory or placement of the implants.

The presacral access tract traverses posterior to the bowel and anterior to the sacrum. Possible access risks include infection due to bowel injury and bleeding due to injury to presacral veins or the middle sacral artery. Fluoroscopic monitoring, rectal air insufflation, blunt access instruments, and dilation rather than sharp dissection into the sacral face lessen these risks. The sacral entry site at S1-S2 is a relatively bare area in the pelvis, as the major neural and vascular structures are lateral to the midline at this point.

In the spine itself, there is a risk to the spinal canal contents if the trajectory into the disc space is inappropriate or if rotational cutting tools used for discectomy are oversized. As with all image-guided operations, careful attention to landmarks is imperative to minimize the risk of complications.

The sympathetic plexus is usually situated across the L5-S1 interspace. Injury to this structure may lead to retrograde ejaculation. By virtue of the S1-S2 anatomic entry point into the sacral promontory, the risk of injury to the sympathetic plexus is minimized.

Conclusion

The paracoccygeal transsacral exposure technique represents another option for minimally invasive access to the lumbosacral junction. This approach utilizes instruments to enable fusion and stabilization principles to facilitate primary lumbar fusions (Fig. 9.12) or extensions of long

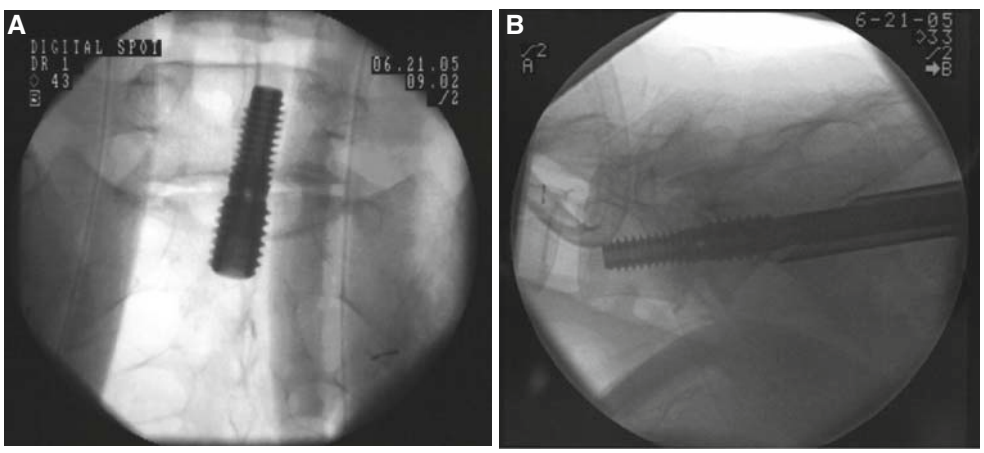

Fig. 9.11 Intraoperative final fluoroscopic image of axial rod implanted. (**a**) AP view, (**b**) lateral view

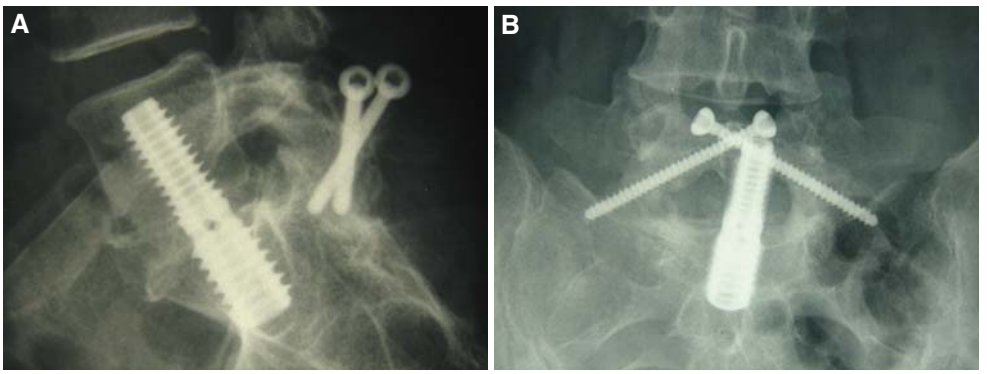

Fig. 9.12 (**a, b**) Example of primary L5-S1 lumbar fusion

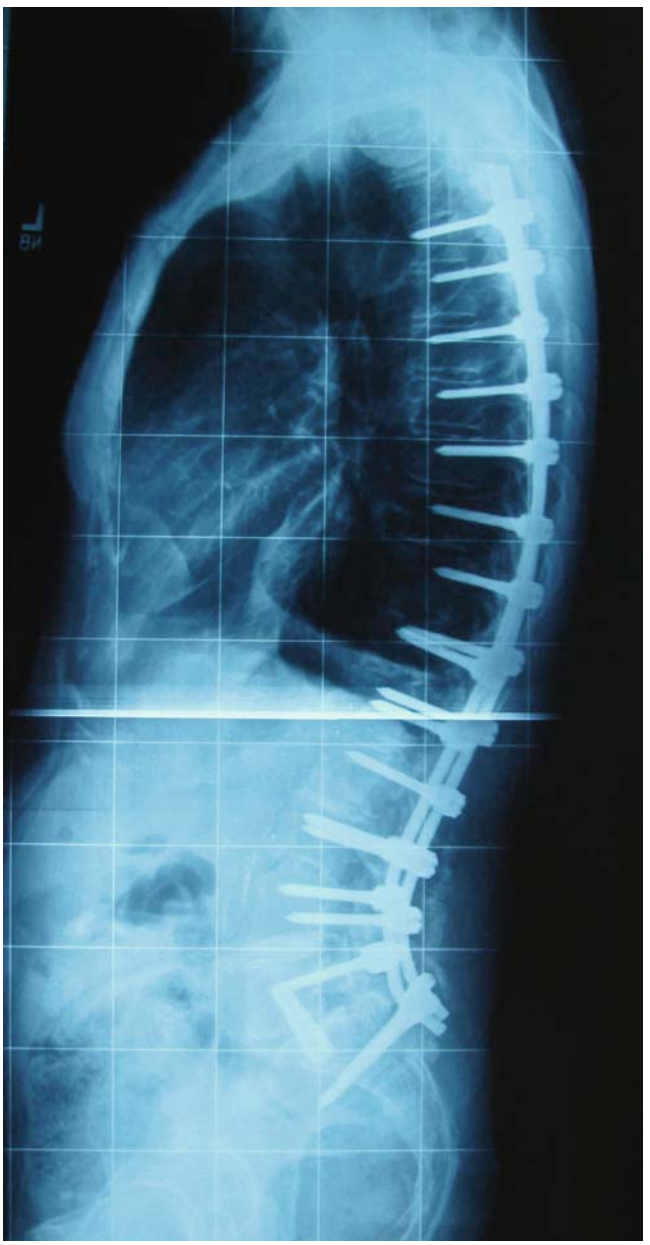

Fig. 9.13 Example of extension of previous long scoliosis fusion across the lumbosacral junction

fusions (Fig. 9.13) across the lumbosacral junction, while minimizing the soft tissue trauma associated with traditional lumbar fusion through open surgical techniques.

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Facet Joint Anatomy and Approach for Denervation

10

Ralph F. Rashbaum and Donna D. Ohnmeiss

Introduction

One of the difficulties in treating back pain is the multiple potential sources of pain, especially those occurring in the same general region. Pain in the low back or buttock may arise from muscle, disc, facet joints, sacroiliac joints, ligaments, etc. Trying to differentiate which structure(s) is responsible for pain presents a challenge. Once identified, the challenge of a viable treatment remains. Similar to the disc, the facets were traditionally thought to have a role in pain production by compressing the nerve roots. Not until years later did the innervation of these structures as well as the role of inflammatory mediators receive attention, and only then did an appreciation for these structures as primary pain generators come about. A spinal segment has frequently been described as a three-joint complex involving the intervertebral disc and the two facet joints. Based on biomechanical theory, many had accepted that facet degeneration is often a secondary occurrence following disc degeneration with a lesser incidence of primary facet injury or degeneration. However, in several studies, there does not appear to be a strong relationship between disc degeneration and facet abnormalities [1, 2].

As early as 1911, Goldthwait recognized the facet as a potential source of pain [3]. Rees first reported on facet denervation in 1971 [4]. In 1974, Shealy introduced percutaneous radiofrequency facet denervation [5].

The occurrence of facet syndrome is 17–20%. Its role may be of increasing importance considering the great number of motion-preserving implants that are being developed and used. If the disc is replaced by a prosthesis, the results may be compromised by an undiagnosed facet problem. In the past, when such a segment would have been fused, a potential facet problem would not have been so important, since the fusion would render the joint, including the facets, motionless.

Indications

One of the most important considerations for successful facet joint denervation is patient selection. Although some authors have reported a relationship between some clinical findings and facet joint problems [6, 7], to date, there is no reliable clinical evaluation for differentiating pain arising from a facet joint from that arising from other spinal structures [8–11]. There is no radiographic or physical examination that can completely and unequivocally identify a facet syndrome. The only indications for rhizotomy are a properly performed facet injection or medial branch block. With the block, the medial branch of the posterior rami, which innervates the facet joint, is anesthetized. Using fluoroscopic control, a small test injection with contrast is used to verify the location. A small amount of anesthesia, approximately 0.3–0.5 cc, is injected into the specific site of the medial branch of the posterior primary ramus. This is done to each of the medial branches, innervating the specific joint to be treated. In order for the block to be considered diagnostic, at least 70% of the patient's pain should be relieved. The use of a comparative block has been advocated to increase the accuracy of the diagnostic evaluation. This is to be done at a separate time.

The literature dealing with the diagnostic accuracy of facet injections and blocks as well as rhizotomy has been inconsistent. A recent comprehensive review by Boswell et al. found that there was moderate evidence to support facet joint interventions [12]. One difficulty with the literature is that the technique or selection criteria for the procedures are inappropriate or not described well enough to determine the appropriateness. In the case of denervation, one study based the indications on clinical

R.F. Rashbaum (✉)
Texas Back Institute Research Foundation, Plano, TX 97093, USA
e-mail: rrashbaum@texasback.com

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evaluation, not injections. In another randomized study, yielding equivocal results, the needle was placed perpendicular to the target, which decreases the chances of ablating the neural tissue. Only with carefully performed diagnostic injections and meticulous ablation technique can the results of facet rhizotomy be optimized. This can only be achieved through knowledge of the facet anatomy and details of the appropriate technique.

Facet denervation is a treatment for mechanical low back pain and must be done concurrent with an exercise program geared to helping minimize stress on the diseased segment.

Anatomy

The facets represent the articulating joint created by the posterior interface between vertebral bodies and is made of the inferior element of the superior vertebra and the superior element of the inferior vertebra. Their structure is primarily that of a diarthrodial synovial joint covered with hyaline cartilage. The facets play a role in weight bearing, limiting the extent of spinal extension and rotation, and limiting forward sliding of the vertebra. The shape and angulation of the facets vary greatly among individuals. The impact of the anatomical variations in the shape of the joints is not well understood.

In a more recent study of facet joints, Igarashi et al. removed samples of joint cartilage and synovia from patients undergoing surgery for disc herniation or lumbar stenosis [13]. They found high levels of inflammatory cytokines in the facet tissue, such as interleukin-1beta and -6 and tumor necrosis factor-alpha (TNF-alpha). The level was greater in the stenosis patients than in the disc herniation patients. Their results suggest that these inflammatory agents may have a role in explaining pain arising from the facet joint.

Biomechanics

With the increasing options for disc treatments and anterior devices, there has recently been increased interest in the effect of these devices on the biomechanics of the facet joints. The advent of dynamic stabilization devices such as total disc replacements, nucleus replacements, and dynamic posterior stabilization implants has led to a renewed interest in the biomechanics of the facet joints. Also, the impact of fusion as well as these dynamic devices on the role of the facet joint as a pain generator has increased recently.

In a study using a rabbit model, Onodera et al. investigated the effect of anterior fusion on the density and distribution of neural endings in the facet joint [14]. They reported that at the level of the simulated fusion, there were significantly fewer mechanoreceptors at follow-up. At the level of the simulated fusion, there was a significant decrease in the number of nerve endings in the facet joints. At the level above the simulation, the authors suggested that there may be neural sprouting due to nociceptive stimulation.

Innervation

Understanding the innervation of the facet joints is vital to successful denervation. Several authors have described the innervation of the lumbar facet joints [15–18]. From L1 to L4, the dorsal rami divide into two branches. The medial branch innervates the facet joints. Each facet joint is innervated by the branches from two different levels (Fig. 10.1). For example, the L3-4 facet is innervated by the L3 medial branch from the superior level and L4 medial branch from the inferior level. The L5-S1 facet joint is innervated by the medial branch of the L4 dorsal ramus, which crosses the transverse process of L5, and by the dorsal ramus of L5, which crosses the sacral ala. As described by Bogduk, a source of confusion that may arise is in the naming and understanding of which nerves innervate which facet joint [19]. The L4-5 facet joint is innervated by the medial branches of the L3 and L4 dorsal rami, which traverse over the L4 and L5 transverse processes. The numerical identification of the joint to be treated is the same as the transverse processes where the needles shall be placed; however, the nerve names are one less. The L5 dorsal ramus is longer than those at the levels above and courses along the groove between the sacral ala and the superior facet of the sacrum. Along the lower edge of the facet, the ramus divides, and the medial branch innervates the L5-S1 facet.

Denervation Technique

The goal of facet denervation is to ablate the portion of the nerves that innervates the facet joints so that they no longer transfer pain signals. This procedure should not be expected to always be a long-term solution, as the nerve branches grow back in many patients.

As with any treatment, an understanding of the anatomy, the pathophysiology, and the mechanism of action of the treatment along with good technical detail are paramount for a successful treatment outcome.

Fig. 10.1 Anatomy and innervation of the facet joint

Once the level of the facet joint(s) to be denervated has been determined by clinical evaluation and diagnostic injections, planning the procedure can take place. Based on the anatomy, two adjacent levels must be treated in order to denervate one facet joint. This is due to the joint being innervated by two separate dorsal rami branches. The most common treatment involves the use of percutaneous radiofrequency electrodes.

Patient preparation for the procedure includes patient education about the treatment, potential risks, expectations, and postprocedure care, both short- and long-term. When writing a prescription for facet denervation to be performed by someone other than the prescribing physician, the script must be clear. It should include the specific level(s) to be treated and if unilateral or bilateral intervention is needed. Additionally, if the patient has an L6 vertebral body, one must exercise particular care in delineating the level(s) to be treated.

The patient should be intubated and positioned prone on the procedure table (physician's choice). The patient's back should be draped and prepped (Fig. 10.2). At our facility, the patient is given a bolus of Ancef 1 g 30 min before the procedure. For imaging, the fluoroscopic unit

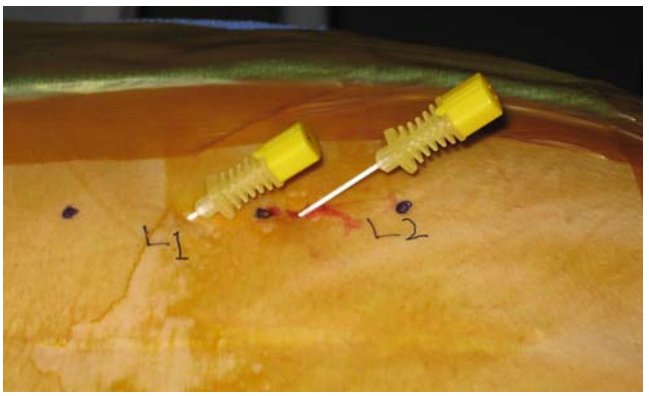

Fig. 10.2 The levels to be treated are marked on the skin, which is prepped and draped for the procedure

is inclined from a caudal to cephalad and oblique angle. A 20-gauge rhizotomy needle with an exposed 10-mm tip is used (Fig. 10.3). In a similar fashion, needles are positioned at the other level(s) to be treated. After all needles have been placed, stimulation is performed to ensure that none of the needles is positioned too near a motor fiber of the anterior primary ramus. Once this is accomplished with up to 2.5 V, the rhizotomy procedure is initiated. The temperature is elevated slowly to 85° and maintained for 60 s (by the radiofrequency generator). After this is accomplished, a mixture of 2 ml of the following is injected: 30 ml of 1% Xylocaine, 30 ml of 0.25% Marcaine, both with epinephrine, and 2 ml of Celesteone. This is to allow for a comfortable transition from the surgical suite to home. At that point, the needle is withdrawn. After the

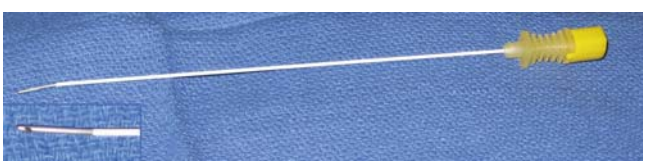

Fig. 10.3 The facet rhizotomy needle. The *inset* shows the angulation of the tip

entire procedure has been completed, the patient is taken to a recovery room. Postprocedure instructions are to proceed with physical activities as tolerated. Patients are informed that bending and twisting movements are to be limited to decrease stimulation of the inflamed area. The patient is seen in two to three weeks for a follow-up visit in the clinic.

One of the most important aspects of having a successful outcome from facet denervation is the positioning of the electrode. In a laboratory study of radiofrequency electrodes, the pattern of the lesions created was investigated [20]. The authors found that lesions do not occur at the tip of the electrode, but rather they form an oval around the body of the electrode with an effective radius of only 2 mm. This finding has very significant clinical implications [19, 21]. As Bogduk noted, in many studies, the needle was placed perpendicular, or slightly off-perpendicular, rather than parallel to the nerve. The perpendicular placement would compromise the overall results of the procedure in that the nerve may not have been coagulated or only partially lesioned. This may result in no, or only partial, pain relief.

One structure that is sometimes overlooked is the mamillo-accessory ligament (Fig. 10.4). This ligament is generally nonconsequential clinically, but one should be aware of its potential role in effecting denervation procedures. It should be taken into account that the medial branch of the dorsal ramus passes under the mamillo-accessory ligament. At that point, the medial branch is not accessible for ablation. Therefore, attempted coagulation of the branch in this vicinity will inevitably be fruitless since the ligament is between the needle and the nerve. Figure 10.5 shows the oblique and AP views of the needles positioned for the denervation.

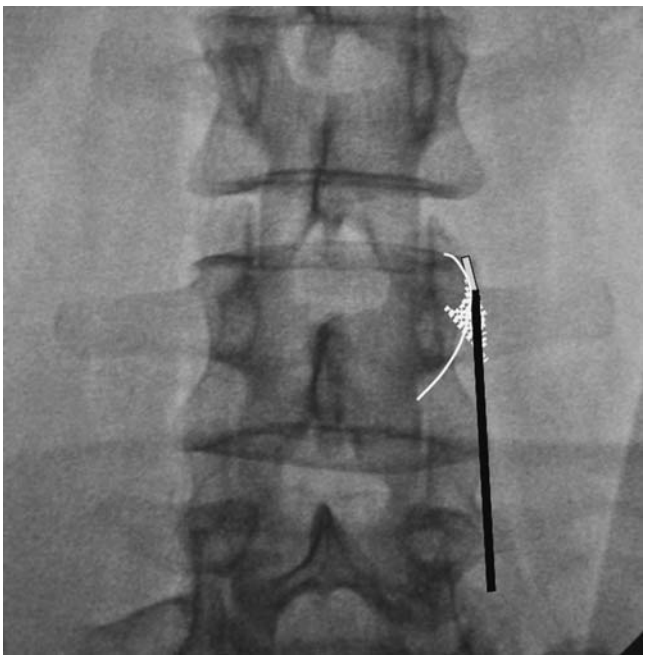

Fig. 10.4 The medial branch (*white curve*) crosses under the mamillo-accessory ligament (represented by the *white dotted lines*). The curved tip of the rhizotomy probe is placed along the medial branch at a point before it passes under the mamillo-accessory ligament

Derby and Lee, using a porcine model, investigated the use of two needles simultaneously to determine if this would increase the area of the lesion [22]. They placed two needles parallel to each other and parallel to the nerve. The probes were heated simultaneously. The authors found that this technique provided a greater area of coagulation than did a single probe or heating the probes individually. Clinically, this may suggest that this technique may be related to an enhanced clinical result due to a reduced risk of missing the target area, or only partially coagulating the neural tissue.

Complications

As with any intervention, facet denervation does have a risk of complications. Sowa identified potential complications that should be discussed with the patient prior to the procedure, include bleeding, infection, theca sac puncture and headache, allergic reaction, vasovagal reaction, and permanent damage to the spinal nerve with resulting sensory and/or motor loss [23]. Another potential complication is skin burns.

There have been few studies addressing the safety of fluoroscopic radiofrequency facet denervation. Kornick et al. reported a retrospective review of this procedure at a total of 616 facet joints [24]. They found six minor complications (1.0% incidence). These included three cases of localized pain lasting more than two weeks, and three cases of neuritic pain lasting less than two weeks. There were no infections and no cases of new motor or sensory deficits.

Discussion

The effectiveness of facet joint denervation has been disputed. As with many spinal procedures, there are likely several reasons for the disparity. Diagnosing facet joint problems is not a simple process. The clinical symptoms overlap with pain from other spinal origins, and patients may have pain arising from more than one structure, such

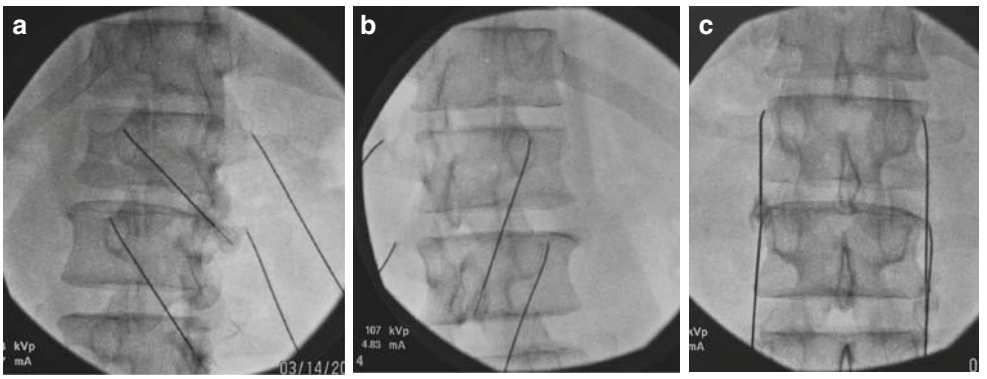

Fig. 10.5 (**a–c**) Oblique and AP views showing the placement of the needles at the L1 and L2 vertebral bodies. Note the positioning parallel to the course of the nerves to the lesioned

as bilateral facet joints, facets at multiple levels, and combinations of facet and disc degeneration at the same or different lumbar levels. The primary diagnostic evaluation for facet joint pain is a facet injection. As with discography in the diagnosis of disc-related pain, the value of facet injections as a diagnostic procedure is only as good as the technique used.

It should be understood by physicians and patients that medial branch denervation is likely not a permanent treatment. However, as reported by Schofferman and Kine, repeat neurotomy can be successful [25]. In their study, the favorable effect of the initial treatment lasted for a mean of 10.5 months. Among the patients with a successful initial treatment, about 85% had a successful result from subsequent treatments. The mean period of relief after these subsequent neurotomies was about the same as for the initial treatment.

Facet joint denervation can yield favorable results in appropriately selected patients, that is, those who have had complete or almost complete relief from an appropriately performed facet joint injection or block. Clinical evaluation, that is, physical examination such as range of motion and extension-rotation movements, is an inadequate evaluation to determine candidacy for rhizotomy. Also, the denervation procedure itself must be performed with careful attention to the details of the technique. In particular, imaging should be used in multiple planes to determine the needle position. One must be aware of the mamillo-accessory ligament, which the medial branch passes under, rendering ablation useless. Also, with the majority of needles used for denervation, the needle must be positioned parallel and adjacent to the target tissue; otherwise, only partial or minimal ablation can be achieved. Physicians interested in performing facet denervation procedures should invest time being mentored by those who are extremely familiar with facet joint innervation and well experienced in performing these procedures.

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Facet Joint and Epidural Injections

11

Mark S. Wallace and Tobias Moeller-Bertram

Facet Joint Injections

Anatomical Considerations

The facet or zygopophyseal joints are true diarthrodial joints with a synovial membrane rich in neuropeptide-containing free nerve endings [1]. They are formed by the articulation of the inferior articular process of the vertebra above with the superior articular process of the vertebra above.

Cervical facet joint innervation: The innervation of the cervical facet joints is more complex than the lumbar or thoracic region. The medial branches of the C4–C7 dorsal rami wrap around the waist of their respective vertebra and provide articular branches to the facet joint above and below the nerve before entering into the multifidus muscle [2]. The C3 dorsal ramus divides into a medial branch that supplies part of the C3-4 facet joint and a large third occipital nerve that supplies the C2-3 facet joint.

Thoracic facet joint innervation: The thoracic facet joints are innervated by the medial branches of the thoracic dorsal rami. The nerve crosses over the junction between the superior articular process and the transverse process of the vertebra one segment below (see discussion under lumbar facet joint innervation for an example). It has been suggested that the thoracic medial branches cross over the superolateral corners of the transverse process and then pass medially and inferiorly across the posterior surfaces of the transverse processes before entering the multifidus muscle [3]. This description places the medial branch laterally.

Lumbar facet joint innervations: With the exception of the L5-S1 facet joint, each lumbar facet joint receives innervation from the medial branch of the dorsal ramus. The L5-S1 facet joint is innervated by the dorsal ramus itself [4–6]. Each lumbar facet joint is innervated by the medial branch above and below the joint. The lumbar medial branch courses over the junction between the superior articular process and the transverse process of the vertebrae one segment below. For example, the L3 medial branch crosses the junction between the superior process and transverse process of L4. The nerve passes under the mamillo-accessory before crossing the vertebral lamina, where articular branches are given to the facet joints above and below the nerve [7]. The nerve then passes into and innervates the multifidus muscle.

M.S. Wallace (✉)
Department of Anesthesiology, Center for Pain Medicine, University of California-San Diego Medical Center, La Jolla, CA 92037, USA
e-mail: mswallace@ucsd.edu

Indications

1. Spinal pain of more than three weeks' duration with or without associated extremity pain.
2. Documented clinical findings, which may include the patient's pain being reproduced on moving the joint, especially in the cervical area.
3. Increased muscle tone over the joint.
4. Pain in a recognized joint referral zone.
5. Maximal site of tenderness over the joint area.
6. Failure of appropriate conservative therapy, which includes mobilizations or manipulation of the joint by a physical therapist or chiropractor. Passive modalities such as heat, ultrasound, gentle massage, and exercise are not considered appropriate.

Technique

Facet joint and medial branch blocks should be done utilizing fluoroscopy. The medial branch block has been reported to have a similar specificity as intraarticular

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injection for diagnostic purposes [8, 9]. For diagnostic injections, sedation should be avoided or minimized, as the medications administered may interfere with the interpretation of the block. Oral Valium 10 mg 20 min prior to the injection is usually sufficient and should not interfere with the diagnostic interpretation of the injection.

Intraarticular Facet Injections

Cervical

The approach can be either lateral or from the posterior (Figs. 11.1 and 11.2). If posterior, the C-arm needs to be positioned in a caudal-cephalad direction so the joints are clearly outlined. The needle has to pass through the muscles of the neck, and thus, this approach tends to be more painful. The lateral approach has the advantage of the joints being very close to the surface and is less painful. The introduction of a 22- or 25-gauge spinal needle is done with the needle first contacting the body of the joint and slowly walking off it into the joint itself. Verification of intraarticular spread is made with 0.1 cc of contrast. The injectate volume should be less than 0.5 ml of local anesthetic with or without steroid. The atlanto-occipital joint and the atlantoaxial joint require special expertise to avoid the vertebral artery and are not discussed here. Injection of even small amounts of local anesthetic into the vertebral artery can result in cardiorespiratory arrest. Injection of particulate steroid into the vertebral artery can result in serious cerebellar-basilar infarcts.

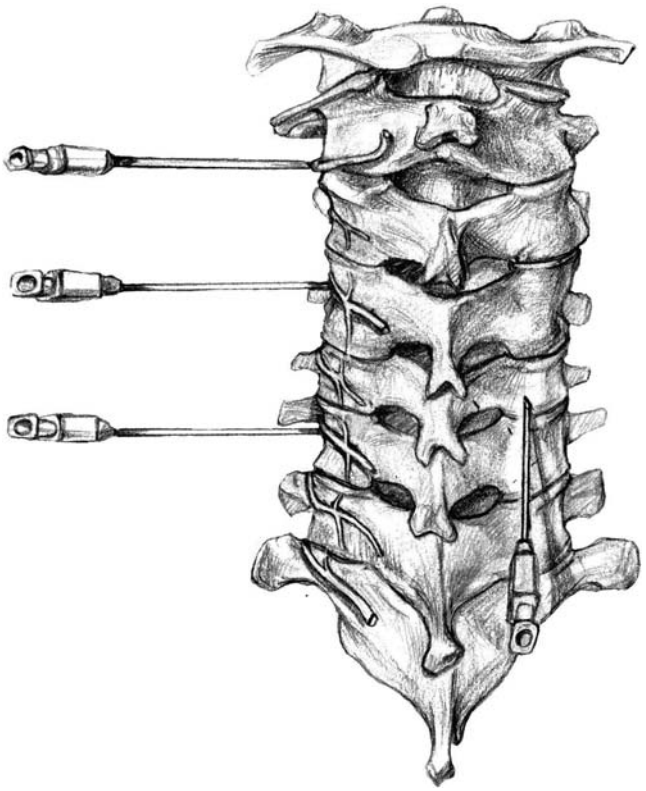

Fig. 11.1 Anterior-posterior view of the cervical spine showing the needle placement for cervical medial branch blocks (*left three needles*) and cervical intraarticular facet injection (*right needle*). Cervical facet medial branch blocks are performed by advancing the needle from a lateral position until contact is made on the lateral pillars of the respective lamina. For the C2-3 facet joint, the third occipital nerve and the C3 medial branch are blocked. The third occipital nerve runs across the mid-portion of the C2-3 facet joint (*top left needle*). The C3 medial branch runs parallel with the lateral pillars of the C3 vertebral lamina. Complete denervation of a cervical facet joint requires blockade of the medial branch above and below the joint

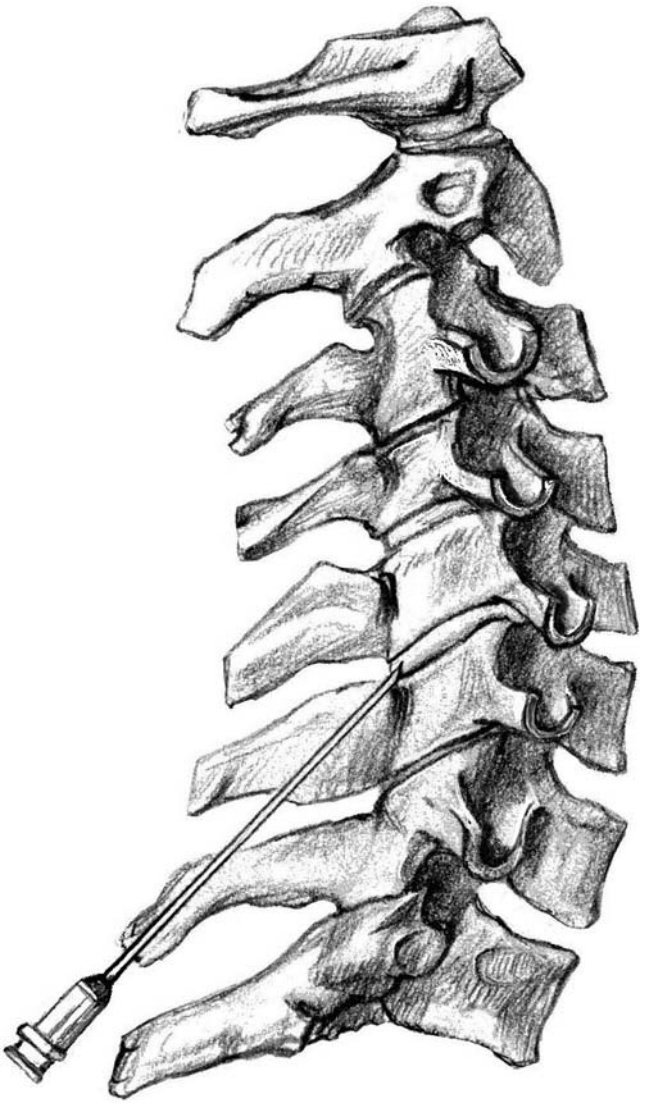

Fig. 11.2 Lateral view of the cervical spine showing an intraarticular needle placement using the posterior approach. Intraarticular placement of the needle can also be accomplished using the lateral approach

Thoracic

With the fluoroscopy in the AP position over the thoracic spine, a 22- or 25-gauge spinal needle is introduced at a level one lower than the C-joint to be blocked. Placing the needle parallel to the spine, approximately 1 cm from the spinal process, the needle is introduced onto the lamina just inferior to the joint to be blocked. Turning the bevel of the needle downward, the needle is gently advanced along the lamina until it catches onto the coronally placed joint. Confirmation of intraarticular positioning can be made with a lateral view. This lateral view is often difficult to identify because of overlying ribs. An injection of 0.1–0.2 cc of contrast demonstrates the round discoid shape of the zygopophyseal joint (Z-joints) on an AP appearance. Injectate containing local anesthetic with or without steroid in a volume of 0.5 cc can then be introduced. If present, concordant pain should be noted during the injection.

Lumbar

With the fluoroscopy positioned cephalad/caudad until the vertebral body endplates of the respective vertebral body are aligned and oblique until the joint line is clearly visualized, a 22- or 25-gauge spinal needle is introduced over the joint in line with the fluoroscopy (gun barreling). The needle is placed on the joint and gently walked into the joint capsule (Fig. 11.3). An injection of 0.1–0.2 cc of contrast verifies intraarticular placement. Injectate containing local anesthetic with or without steroid in a volume of 0.5 cc can then be introduced. Concordant pain, if present, should be noted during the injection.

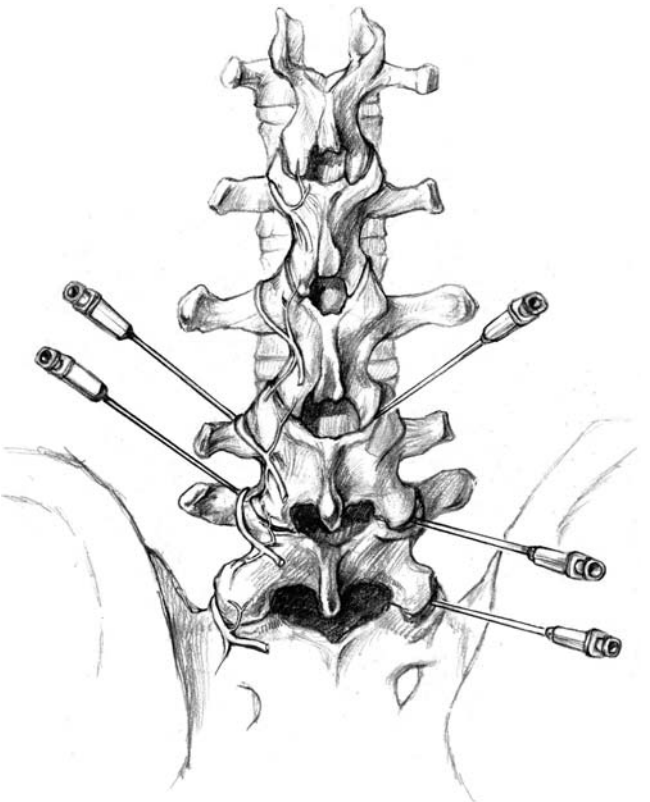

Fig. 11.3 Anterior-posterior view of the lumbar spine showing needle placement for lumbar medial branch blocks (*left three needles*) and lumbar intraarticular facet injection (*right three needles*). Lumbar facet medial branch blocks are performed by using an oblique view and advancing the needle until contact is made at the base of the superior articular process of the respective vertebrae. Complete denervation of a lumbar facet joint requires blockade of the medial branch above and below the joint. For instance, blockade of the L4-5 facet joint requires blockade of the L3 and L4 medial branches. The L3 and L4 medial branches run across the base of the superior articular process of L4 and L5, respectively

Medial Branch Blocks

Cervical

The cervical medial branch of the dorsal primary ramus position is well described and occurs in a consistent position [8]. With a lateral approach, the Z-joints of C3-4, 4-5, 5-6, and 6-7 are anesthetized by injecting 0.5 cc of local anesthetic onto the waist of the articular pillar of the same-numbered vertebrae (Fig. 11.1).

Thoracic

The best place to block the medial branch at the thoracic spine is at the junction of the superior facet and transverse process (Fig. 11.4). This is as it comes off the ventral nerve over the base of the transverse process below its level of origin. The fluoroscopy is positioned cephalad/caudad until the vertebral body endplates of the respective vertebral body are aligned and oblique until a three-line configuration consists of, from lateral to medial, the anteromedial lung margin, the posterolateral margin of the vertebral body, and the posteromedial lung margin. A 22- or 25-gauge needle is advanced until it hits the transverse process at the medial junction of the process and the base of the superior articular process. Like the lumbar region (see discussion below), each joint is innervated by at least two medial branches. It is thus necessary to block two adjacent levels. To block the T4-5 Z-joint, the T3 medial branch and the T4 medial branches need to be blocked as they go across the transverse process of T4 and T5, respectively.

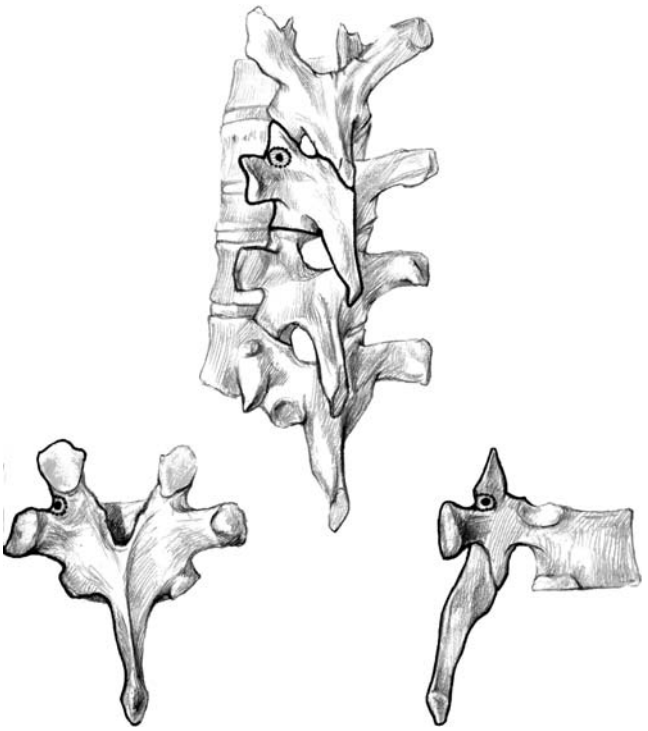

Fig. 11.4 Anterior-posterior (*bottom left*), lateral (*bottom right*), and oblique (*top middle*) views of the thoracic spine showing the target for a thoracic facet medial branch block. Note the target is at the base of the superior articular process of the respective vertebrae. Complete denervation of a thoracic facet joint requires blockade of the medial branch above and below the joint

Lumbar

The best place to block the medial branch at the lumbar spine is at the junction of the superior facet and transverse process (Fig. 11.3). This is as it comes off the ventral nerve over the base of the transverse process below its level of origin. With the fluoroscopy positioned cephalad/caudad until the vertebral body endplates of the respective vertebral body are aligned and oblique until the joint line is clearly visualized, a 22- or 25-gauge needle is advanced until it hits the transverse process at the medial junction of the process and the base of the superior articular process. This point is called the "eye of the Scotty dog," which is located over the pedicle of the respective vertebrae. Each joint is innervated by at least two medial branches. It is thus necessary to block two adjacent levels. To block the L4-5 Z-joint, the L3 and L4 medial branches need to be blocked as they go across the transverse process of L4 and L5, respectively. The L5 medial branch going to the L5-S1 Z-joint is blocked at the notch formed by the superior articular process of S1 and the ala of the sacrum. The L5-S1 joint also receives a small branch from the dorsal ramus of S1 as it emerges from the S1 posterior foramen.

Complications

1. Transient increase in pain
2. Subarachnoid injection
3. Infection
4. Transient dizziness with blockade of the C2-3 facet.

Epidural Steroid Injections

Anatomical Considerations

The epidural space lies between the osteoligamentous structures of the vertebral canal and the dura mater that surrounds the thecal sac. The thecal sac extends from the foramen magnum to about the S2 level. The epidural space extends from the foramen magnum to the sacral hiatus. The contents of the epidural space include nerve roots, epidural fat, epidural veins, and radicular arteries entering the space via the neural foramen.

When passing a needle in the midline between the spinous process, the following structures are encountered: (1) skin, (2) subcutaneous fat, (3) supraspinous ligament, (4) interspinous ligament, and (5) ligamentum flavum. The distance between the ligamentum flavum and dura mater is greatest in the lumbar region (4–6 mm), followed by the thoracic region (3–5 mm), followed by the cervical region (2–4 mm).

The epidural space can be accessed at multiple levels of the spinal column, including between the spinous processes (midline approach), between the lamina (interlaminar approach), through the sacral hiatus (caudal approach), and through the neural foramen (transforaminal approach). Each approach has different levels of risk, which are discussed below.

Indications

1. Back pain that radiates into an extremity with dermatomal sensory changes
2. Clinically significant herniated disc
3. Postural low back pain with intermittent symptoms of extremity pain, numbness, and weakness (this may represent intermittent leakage of the disc contents onto the nerve root)
4. Cancer metastasis to the spine, where the invasion of nerve roots by tumor cells causes an inflammatory response and radicular symptoms.

Technique

Cervical

Interlaminar Approach

Cervical epidural injections carry obvious risks of spinal cord injury, a risk that is a lot lower with the low lumbar epidural injections. Therefore, extra care must be taken in order to avoid this complication. First, cervical epidural injections should always be performed under the guidance of fluoroscopy. Second, the C7–T1 interspace should be used since the epidural space is thickest and the distance from the ligamentum flavum and cord is greatest at this level. Third, the ligamentum flavum is often unfused in the midline, making the midline approach and loss-of-resistance technique not as reliable as when performed in the lumbar region (see discussion below under lumbar).

The procedure is performed with the patient in the prone position with pillows under the patient's chest and the head slightly flexed. Flexion of the neck moves the cervical cord enlargement more cephalad, resulting in a widening of the epidural space at the C7–T1 level. The injection should be performed off the midline on the side of the pain. The location of the upper border of the lamina of T1 should be marked on the skin. A 20-gauge Touhy needle is advanced until the upper edge of the lamina is contacted. At this point, after negative aspiration, a small amount of additional local anesthetic can be injected through the Touhy needle to anesthetize the highly innervated periost. The needle is then carefully advanced off the superior edge of the lamina, and using the loss-of-resistance technique to saline, the epidural space is entered. Correct placement can be verified by the injection of 1–2 cc of water-soluble contrast. Using a pig tail connecter to do so can minimize inadvertent needle movement and enables one to inject the contrast under live fluoroscopy.

The steroid (betamethasone, triamcinolone, methylprednisolone, or dexamethasone) can be diluted in either saline or local anesthetic (about 5 cc) and administered. The risks of using local anesthetic may outweigh the benefits, and there is an argument that the steroid should be diluted in saline to avoid the risk of subarachnoid injection of local anesthetic and total spinal anesthesia.

Transforaminal Approach

The transforaminal approach carries the risk of entering the radicular and vertebral arteries. Therefore the use of particulate steroid is contraindicated. The injection of particulate steroid into either of these arteries can result in catastrophic damage to the spinal cord or brainstem. The steroid of choice for this procedure is decadron.

The procedure is performed with the patient in the supine position. The C-arm is aligned in the anterior oblique view until the neural foramen is clearly visualized. A 25- or 22-gauge needle should be advanced to the posterior aspect of the target foramen. At this location, the needle should be posterior to the vertebral artery. The superior articular process is contacted, and then the needle should be gently advanced into the foramen under anterior-posterior fluoroscopic guidance, being careful that the needle does not enter the vertebral canal. Volumes of 1 cc or less of steroid should be injected.

Lumbar

Interlaminar Approach

The procedure is performed with the patient in the prone position. The injection should be performed off the midline on the side of the pain. The location of the upper border of the lamina of vertebral level to be injected should be marked on the skin. A 20-gauge Touhy needle is advanced until the upper edge of the lamina is contacted. At this point, after negative aspiration, a small amount of additional local anesthetic can be injected through the Touhy needle to anesthetize the highly innervated periosteum. The needle is carefully advanced off the superior edge of the lamina, and using the loss-of-resistance technique to saline, the epidural space is entered. Correct placement can be verified by the injection of 1–2 cc of water-soluble contrast. Using a pig tail connecter to do so can minimize inadvertent needle movement and enables one to inject the contrast under live fluoroscopy.

The steroid (betamethasone, triamcinolone, methylprednisolone, or dexamethasone) can be diluted in either saline or local anesthetic (about 5 cc) and administered. The risks of using local anesthetic may outweigh the benefits, and there is an argument that the steroid should be diluted in saline to avoid the risk of subarachnoid injection of local anesthetic and total spinal. However, the risks of using local anesthetic in the lumbar region are much lower than when it is used in the cervical region.

Transforaminal Approach

The procedure is performed with the patient in the prone position. The fluoroscopy is aligned in the cephalad-caudad direction until the anterior and posterior endplates of the respective vertebral body are aligned. An oblique view is

then made until the pedicle of the respective vertebral segment is visualized end-on. A 25- or 22-gauge needle should be advanced to the "6 o'clock" position of the pedicle, which is located in the "safe triangle." The borders of the triangle are (1) the pedicle above, (2) the nerve root medial, and (3) the lateral edge of the vertebral foramen. An injection of contrast (0.5 cc) should fill the vertebral foramen and spread along the nerve root into the epidural space. This is followed by 1 cc or less of steroid (betamethasone, triamcinolone, methylprednisolone, or dexamethasone).

Caudal

The patient is placed in the prone position. The cornua of the sacrum are identified. The two cornua usually form the lower border of the sacral hiatus, which is covered by a thick ligament. A 20-gauge needle is advanced into the sacral hiatus. The placement can be guided by a lateral fluoroscopic view of the os sacrum showing the entry of the hiatus between the bony plates (Fig. 11.5). Usually, a distinct give will be felt in the needle as it enters the epidural space. Correct placement can be verified by injection of 1–2 cc of contrast followed by steroid (betamethasone, triamcinolone, methylprednisolone, or dexamethasone) diluted in 5 cc of saline or local anesthetic.

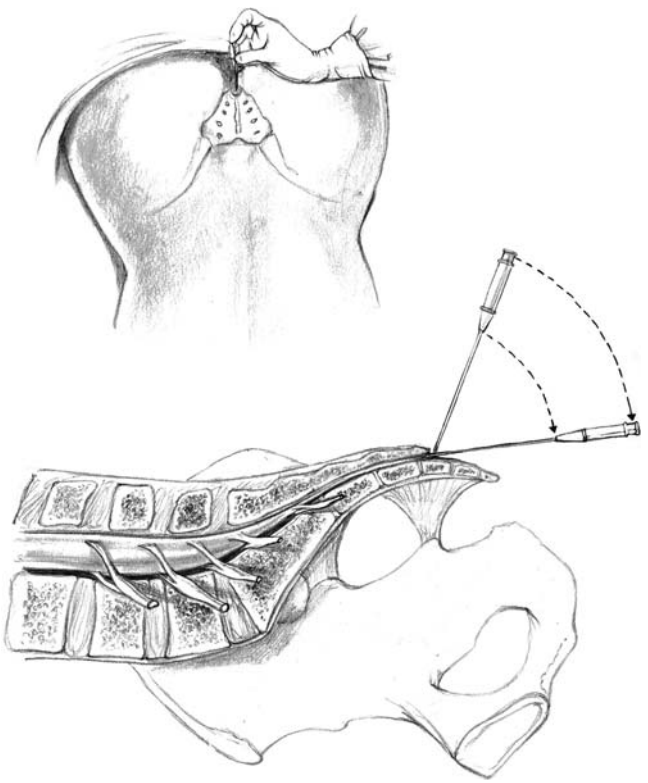

Fig. 11.5 Anterior-posterior (*top*) and lateral (*bottom*) view of a caudal epidural steroid injection. The needle is advanced through the sacral hiatus into the epidural space using a 45° needle angle. Once the ligament is penetrated, the needle angle is reduced and the needle slightly advanced into the epidural space

Complications

1. Dural puncture and postdural puncture headache
2. Transient increase in pain
3. Vertebral artery injection (with cervical transforaminal injections)
4. Spinal artery injections (with transforaminal injections)
5. Subarachnoid injection
6. Nerve root trauma (with transforaminal injections)
7. Infection.

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Discography and Endoscopic Lumbar Discectomy

12

Michael A. Chang, Christopher A. Yeung, Anthony T. Yeung, and Choll W. Kim

Introduction

One of the most common treatments for lumbar radiculopathy is discectomy. Since 1938, open discectomy has been used to relieve pain caused by herniated discs. The success rate for this operation has been satisfactory, but complications may occur, including bleeding, prolonged pain, and scar formation. Furthermore, the soft tissue dissection and bony resection required to gain access to the disc herniation may lead to segmental instability.

Minimally invasive techniques such as endoscopic discectomy have been developed over the past 10 years and provide an opportunity to avoid the potential morbidity of traditional open surgery. The early techniques were lacking in standardization and training in academic centers, dependent on surgeon champions who adapted the approach using simple endoscopes and instruments. The lack of instrumentation also made the procedure technically demanding. Over the past 8–10 years, major improvements in instrumentation and technique have been made, and their use of is gradually increasing in acceptance. The proponents of the endoscopic approach report less skin and muscle trauma, maintenance of bony integrity, and minimization of nerve root trauma, which may translate into quicker recovery [1]. Most series reports indicate outcomes equivalent to those of open discectomy, but with less surgical morbidity [1–5].

M.A. Chang (✉)
Department of Orthopedic Surgery, Wichita Clinic, Wichita, KS 67206, USA
e-mail: mchangrochester@yahoo.com; changma@wichitaclinic.com

Endoscopic Discectomy Technique

Indications/Contraindications

Currently, the best indication for the use of an endoscopic poste rolateral approach to the lumbar spine is for an extraforaminal far-lateral disc herniation. Experienced endoscopic surgeons also include contained central and paracentral disc herniations, foraminal herniations, recurrent herniations, small nonsequestered extruded disk herniations, synovial cysts, biopsy and debridement of discitis, decompression of foraminal stenosis, visualized total nuclectomy (prior to nucleus replacement), and visualized discectomy and endplate preparation prior to interbody fusion or total disc replacement (TDR) implantation. A unique advantage of this approach that expands its indications stems from this technique's efficacy when routinely used with local anesthesia. Patients with any of the fore-stated pathology who are "too high-risk" to withstand the morbidity of general anesthesia are excellent candidates for this very safe approach.

Contraindications, which are considered relative, may include some extruded sequestered disc herniations or extruded migrated disc herniations that are out of reach of the foraminal approach or are better addressed by a traditional approach. The relative indications/contraindications are dependent on the surgeon's experience and skill in accessing the epidural space in each individual patient. The technique is especially valuable for recurrent or primary disc herniations with associated epidural scarring. Foraminal decompression of moderate central and lateral canal stenosis is also indicated when there is adequate support staff or equipment available to successfully perform the procedure. Contraindications are considered "relative" because the technique depends on technical skill and experience.

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Anesthetic Technique

Although some experienced surgeons worldwide have safely used general anesthesia, when local anesthesia is used as the preferred technique, the proximity of the exiting nerve root within the surgical corridor mandates that the patient be alert enough to verbalize pain throughout the procedure. This precaution decreases the risk of inadvertent nerve injury during needle insertion, passage of the dilating cannulas, and activation of the bipolar electrocautery and holmium laser. Anesthesia consists of 0.5% local lidocaine with epinephrine infiltration, supplemented with conscious sedation. The patient is placed in a prone position on a padded frame on a radiolucent table. Percutaneous posterolateral endoscopic lumbar disc herniation (LDH) excision requires precise placement of the endoscope at the annular window using biplanar C-arm guidance. Three fixed roentgenographic landmarks of the target vertebra (Fig. 12.1) are located using the C-arm: the anatomic center of the disc, the foraminal annular window centered within the mediolateral borders of the pedicle (Kambin's triangle), and the disc inclination line that bisects the disc in the lateral projection. The fourth landmark is a topographic location on the skin window calculated from the disc inclination. The skin window's lateral location from the midline determines the trajectory angle into the foraminal annular window.

Determining Surgical Landmarks

The original method as taught by the senior author (ATY) is to find the four anatomic landmarks. The C-arm is oriented in the posteroanterior imaging position, using a narrow metal rod as a radiopaque locator and ruler, and the midline is marked on the skin surface [Fig. 12.2(a)]. Then the metal rod is placed transversely across the disc under evaluation. The anatomic disc center (quadrant circle, Fig. 12.1) is located where the transverse line crosses the longitudinal midline. The surface marking of the anatomic disc center, identified by the line intersections, is used as the first aiming reference point of that disc in the approach. The Ferguson view, achieved by tilting the C-arm in the posteroanterior position until the beam is parallel to the endplates, provides additional aiming reference when the approaching needle is within the C-arm's viewing field.

To view the inclination of the lumbar discs [Fig. 12.2(b)], the C-arm is rotated to the lateral projection. The metal rod is held along the side of the patient in the parasagittal orientation equidistantly between the contiguous vertebral endplates of the index disc, and the disc inclination line is drawn on the patient [Fig. 12.2(c)]. While the metal rod is held in the same position, the length from the center of that disc to the plane of the posterior skin surface is recorded [Fig. 12.2(d)]. This length is used to determine the lateral distance of the skin window [Fig. 12.2(e)] from the posterior midline.

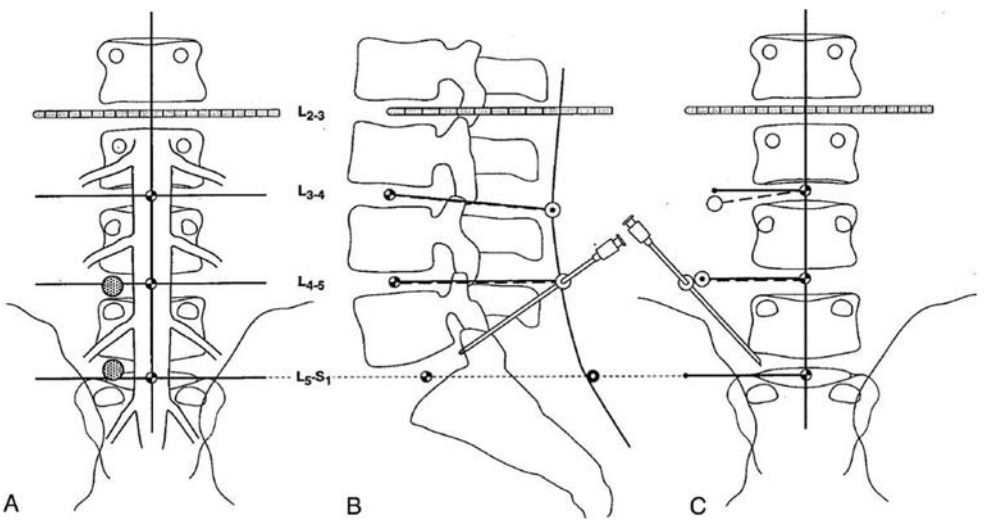

Fig. 12.1 (**a**) Posteroanterior projection. Anatomic disc centers (*quadrant circles*) are located where the horizontal lines intersect the longitudinal midline. The foraminal annular window (*dotted circles*) is centered within the mediolateral borders of the pedicle. (**b**) Lateral projection. The skin window location (*open circles*) is determined at the point where the disc inclination line projects from the plane of the posterior skin. (**c**) Posterior anterior projection. The distance of the L5-S1 disc skin window (*open circle*) from the midline is the same as the distance from the center of the disc to the plane of the posterior skin line on the lateral projection for a central needle location, but a far-lateral skin window and a 10–20° more horizontal trajectory enable easier access to the epidural space and visualization of the traversing nerve root. (Reprinted with permission from Yeung and Tsou [2], Lippincott Williams & Wilkins.©)

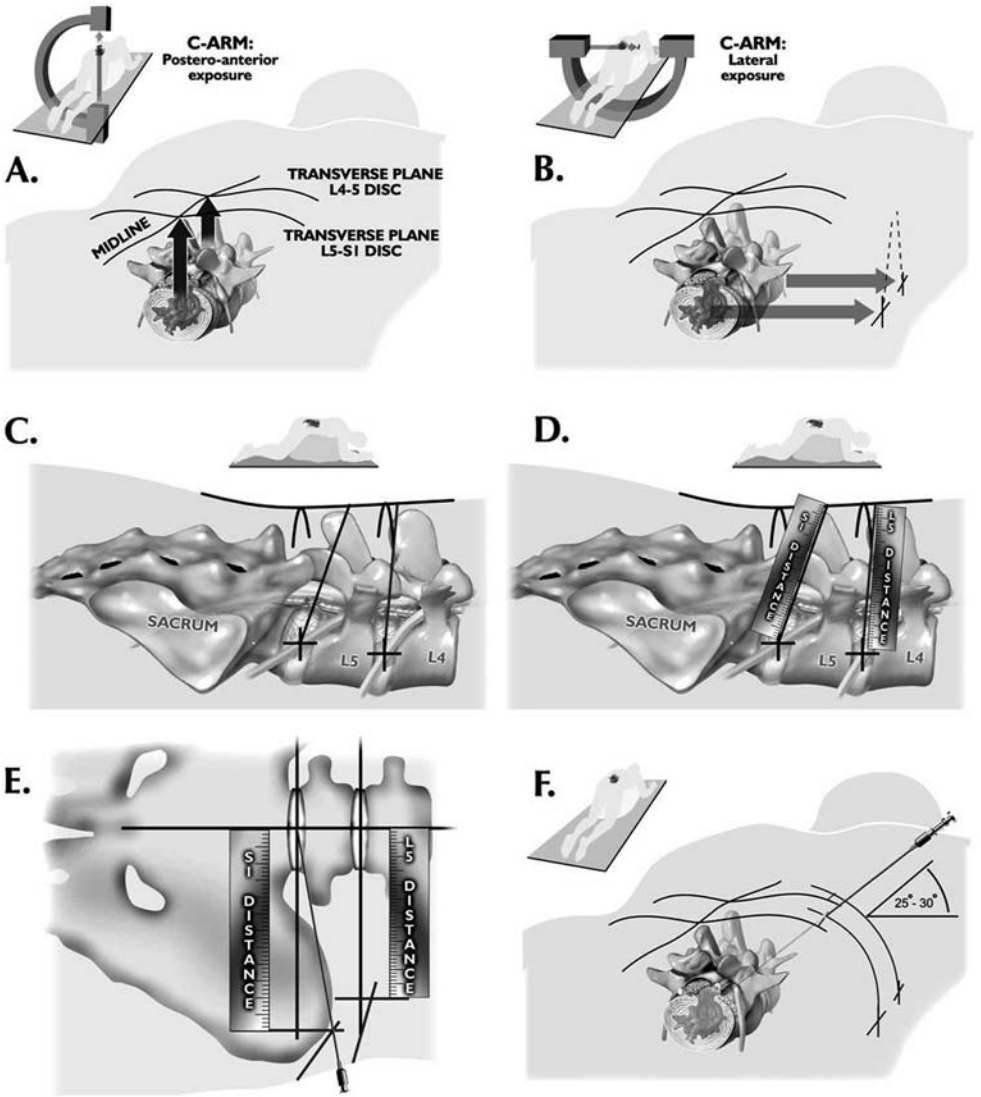

Fig. 12.2 (**a**) The C-arm is oriented in the posteroanterior imaging position, using a narrow metal rod as a radiopaque locator and ruler, and the midline is marked on the skin surface. Then the metal rod is placed transversely across the disc under evaluation. The anatomic disc center is located where the transverse line crosses the longitudinal midline. (**b, c**) The C-arm is rotated to the lateral projection. The metal rod is held along the side of the patient in the parasagittal orientation equidistantly between the contiguous vertebral endplates of the index disc, and the disc inclination line is drawn on the patient. (**d**) While the metal rod is held in the lateral view, the length from the center of that disc to the plane of the posterior skin surface is recorded. (**e**) This length is used to determine the lateral distance of the skin window from the posterior midline. (**f**) The point at which the disc inclination line projects above the posterior skin surface, determined by the metal rod lateral position, is taken as the skin window's cephalad-caudad location. A 6-in.-long, 18-gauge needle is inserted from the skin window at a 25– 30° angle to the parasagittal plane anteromedially toward the anatomic disc center. (Reprinted with permission from Yeung and Tsou2], Lippincott Williams & Wilkins.©)

The point at which the disc inclination line projects above the posterior skin surface, determined by the metal rod lateral position, is taken as the skin window's cephalad-caudad location [Figs. 12.1(b), (c) and 12.2(e)].

The positive disc inclination (lordosis) of the L5-S1 disc is noteworthy. A steep positive inclination will position the skin window above the high iliac crests. A flatly inclined L5-S1 disc in the presence of a high iliac crest requires a more medial placement of the skin window and sometimes a resection of the lateral one fourth of the facet joint. The first neutrally inclined intervertebral disc usually is either L4–L5 or L3–L4. Therefore, the approach angle for the neutrally inclined disc is perpendicular to the midline. A negatively inclined disc, if present, also should be noted. The insertion angle for the negatively inclined L3–L4 disc is cephalad-directed. As the surgeon becomes more experienced and is comfortable performing foraminoplasty and accessing the epidural

space to visualize the traversing nerve root, a far-lateral approach (25–30% more lateral) that levers the cannula against the undersurface of the superior articular process requires a more horizontal approach to the disc. This angle will start the skin window lateral enough to utilize a 10–20° angle rather than the original 20–35° angle in the original technique designed for contained disc herniations. In this projection, the skin window will actually start so far laterally that the needle is actually being inserted ventrally on the patient's back. In an extreme-lateral approach, a CT scan of the abdomen is suggested to avoid injury to the abdominal contents.

Needle Insertion

The skin window, subcutaneous tissue, and trajectory tract are infiltrated using 0.5% lidocaine with epinephrine. A 6-in.-long, 18-gauge needle is inserted from the skin window at a 25–30° angle to the parasagittal plane [Fig. 12.2(f)] anteromedially toward the anatomic disc center. The superficial portion of the needle trajectory usually is outside the C-arm's viewing perimeter. Once the needle tip is visible within the C-arm's viewing perimeter, the C-arm beam can be tilted parallel to the disc inclination (the Ferguson view). The needle is advanced toward the target's foraminal annular window. If minor directional adjustments are necessary, the plane of the needle bevel and the hub pressure are used to redirect. The use of two C-arms for simultaneous biplanar imaging can expedite the needle placement, but it is not necessary if the X-ray technician is familiar with the surgeon's needs.

At the first bony resistance, a patient report of leg pain, or before the needle tip is advanced medially to the pedicle, the C-arm is turned to the lateral projection. The needle tip should not be advanced medially to the pedicle during the initial approach or should advance medially when the needle is advanced. Not monitoring the movement of the needle and interpreting the position of the needle at the first sign of resistance or report of leg pain can result in a trajectory that will injure the exiting nerve root or allow the needle to inadvertently enter the abdomen or the epidural space. Most frequently, the first bony resistance to the needle advancement is from the facet in the path of trajectory. At this point, the trajectory angle must be increased, the needle bevel turned medially, and the approach continued toward the foraminal annular window. The C-arm lateral projection should confirm the needle tip's correct annular location. In the lateral view, the correct needle tip position should be at the posterior vertebral line [Fig. 12.2(b)]. In the posteroanterior view, the needle tip should be centered in the foraminal annular window [Fig. 12.1(c)]. The preceding two views of the C-arm confirm that the needle tip has engaged the safe zone, the center of the foraminal annular window (Kambin's triangle).

The needle is advanced through the full thickness of the annulus. Chromato-discography should be performed at this time to stain the nucleus to further aid the discectomy. The following contrast mixture is used: 9 ml of Isovue 300 with 1 ml of indigo carmine dye. This combination of contrast ratio gives visible radiopacity on the discography images as well as an intraoperative light blue stain of the pathologic nucleus and annular fissures.

Cannula Insertion

A long, thin guidewire is inserted through the 18-gauge needle. The guidewire tip is advanced 1–2 cm deep into the nucleus, after which the needle is removed. The bluntly tapered cannulated obturator is slid over the guidewire until the tip of the obturator has firmly engaged the annular window. An eccentric parallel channel in the obturator allows four-quadrant annular infiltration using small incremental volumes of 0.5% lidocaine with epinephrine in each quadrant, enough to anesthetize the annulus but not the nerves. The obturator is held firmly against the annular window surface and the guidewire is removed. Then the full thickness of the annulus is infiltrated through the obturator center channel with 0.5% lidocaine with epinephrine.

The next step is the through-and-through fenestration of the annular window by advancing the bluntly tapered obturator. Annular fenestration is the most painful step of the entire procedure. The anesthesiologist should be advised to heighten the sedation level just before annular fenestration. However, the patient must be alert enough to detect nerve injury. The entire obturator tip is advanced into the annulus and confirmed on the C-arm views. The beveled-tip access cannula is now slid over the obturator toward the disc. The cannula is advanced until the beveled tip is deep into the annular window.

Discectomy

The foraminal annular window, an easily identifiable C-arm and intraoperative anatomic landmark, is the starting location for endoscopic disc excision. The obturator is

removed, and the operating endoscope is inserted. Through the endoscope the surgeon may see various amounts of blue-stained nucleus pulposus. The general-purpose access cannula has a bevel hypotenuse of 12 mm and an outside diameter of 7 mm. When the cannula is retracted slightly to the mid-straddle position in relation to the annular wall, the wide-angle scope visualizes the epidural space (red), the annular wall (white), and the intradiscal space (blue) in the same field. The visualization of the differentially colored structures is also known as the "red, white, and blue sign" (Fig. 12.3).

The endoscope trajectory from the skin window to the foraminal annular window controls the instrument's accessibility to the epidural space. The 25–30° trajectory in relation to the frontal plane allows the extraction of intracanial contained herniations, whereas the 10–20° trajectory is ideal for most other, central herniations, where the surgeon is able to visualize the epidural space easily but is still able to lever the cannula ventrally by levering it against the superior articular process. The basic endoscopic method for excising a noncontained paramedian extruded lumbar herniation disc is described [Figs. 12.4(a), (b)].

The 25–30° trajectory is used for small to moderate contained herniation extractions. This trajectory is the initial trajectory if the surgeon wants to avoid the morbidity of causing scarring or bleeding in the epidural space when it is sufficient to decompress the base of the herniation. A working tunnel is first created from the foraminal annular window. The excavation is extended to a location just under the apex of the herniation. An endoscopic rongeur is used to extract the blue-stained material in the tunnel. Directly under the herniation's apex, a large amount of blue-stained nucleus usually is present,

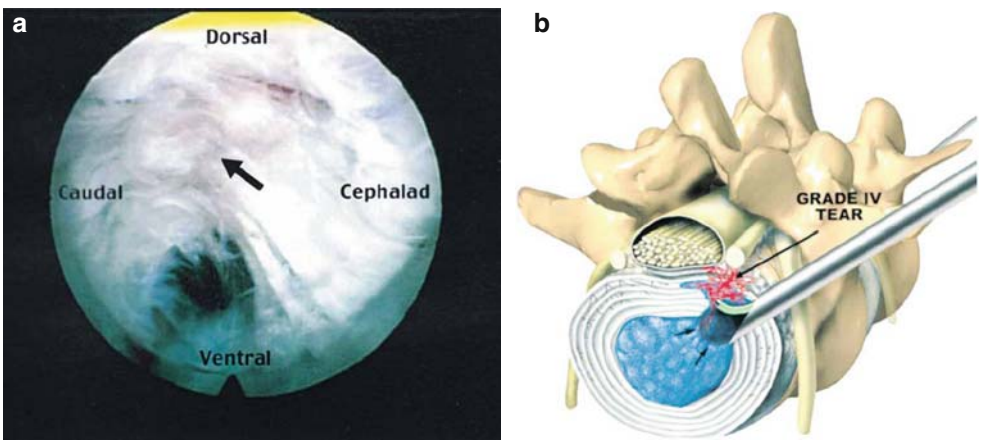

Fig. 12.3 (**a**) Endoscopic view of the *red* epidural space (dorsal), *white* annulus (*arrow*), and *blue* nucleus (ventral). This is known as the "red, white, and blue sign." (**b**) Pictorial representation of the "red, white, and blue sign." (From Tsou et al. [7]. Reprinted with permission from Elsevier.)

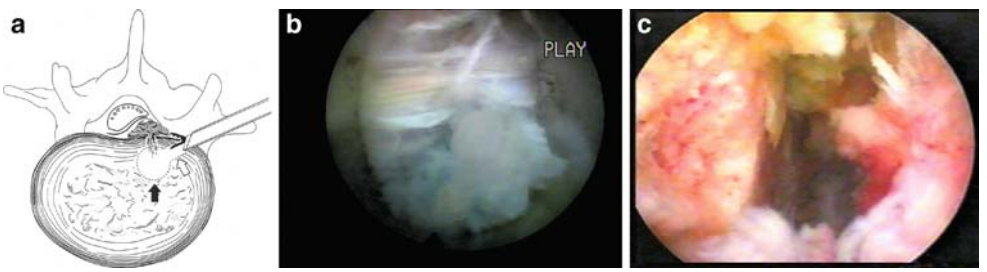

Fig. 12.4 (**a**) Endoscopic excision of paramedian noncontained lumbar disc herniation. From the foraminal annular window, the working tunnel (*open arrow*) and working cavity (*solid arrow*) are excavated. (**b**) Endoscopic illustration of a paracentral HNP. The base of the blue-stained nucleus pulposus is seen extruding into the cannula. The annulus (horizontal fibers) is stretched by the herniation. (**c**) Endoscopic illustration of the working cavity. The *blue*-stained degenerative nucleus has been removed, leaving a portion of the base of the herniation remaining to be decompressed. [Part (a) reprinted with permission from Yeung and Tsou [2], Lippincott Williams & Wilkins.©]

resembling the submerged portion of an iceberg. The nucleus here represents the migrated and unstable nucleus. The movement direction follows the path of least resistance toward the already thinned-out and perforated annulus. A bulk decompression is performed using a motorized shaver. This step requires C-arm localization of the shaver head before power is activated. The cavity thus created is called the "working cavity" [Figs. 12.4(a), 12.4(c)]. The debulking process serves two functions. First, it decompresses the disc, reducing the risk for further acute herniation. Second, it creates a cavity into which the herniated fragment can be pulled to allow its removal (inside-out technique).

If a noncontained extruded disc fragment is confirmed by blue-stained nucleus material found in the epidural space, additional steps are necessary before the epidural part of the herniation is removed. The blue-stained narrow intraannular herniation track and a thin blue dome deep to the herniation track are left undisturbed at this point. The blue-stained intraannular part of the herniated nucleus is a guide leading to the epidural part of the herniation. The annular collar is divided, and a cutting forceps is used to perform the partial annulectomy. The side walls of this annular channel can be widened further by using a side-firing Holmium yttrium-aluminum-garnet (YAG) laser. Any epidural bleeding encountered is controlled by using a wide-sweep, radiofrequency trigger-flex bipolar probe (Ellman Trigger-flex probe, Ellman International, Hewitt, NY). A second endoscope inserted from the contralateral side may be necessary to facilitate the discectomy.

When the aforementioned extended annulectomy has been carried out, the subligamentous or extraligamentous components of the herniation are first extracted into the working cavity and then pulled out through the endoscope's working channel. The reason for pulling the herniated elements into the working cavity first is more apparent in the massive midline herniation. One variant of the massive herniation is the condition in which the annular attachment at one vertebral corner is avulsed, described as an open hinged door. In this condition, a large amount of the nucleus has extruded into the spinal canal. The detached annulus may rotate up to 180° on its remaining attachment to the other vertebral corner. When faced with this situation, the surgeon should proceed to excavate the working tunnel and create a larger working cavity. The Holmium YAG laser is used to divide the intact annular vertebral corner attachment. Once the large nuclear and annular fragments are free, the fragment is pulled first into the working cavity, and then out through the cannula, together with the endoscope.

Discectomy After Previous Surgery

The endoscopic technique in excising an LDH in patients who have undergone prior surgical intervention at the index level requires a modification of the operative technique. The most common reasons for reoperations are either a missed fragment or reherniation after prior surgical intervention. During endoscopic reoperation, the newly herniated nucleus can be anchored firmly to the annular herniation track and the cicatrix stretched over the herniation apex. If the prior intervention was a transcanal approach, the standard working tunnel and working cavity must be created. The forceps is used to perform a partial annulectomy from the annular window toward the herniation fragment [Figs. 12.5(a), (c)]. By removing the intervening tissue, the shape and orientation of the reherniated fragment can be ascertained. If the herniated part is firmly adherent to the annular tract, the laser is used as a dissecting tool. The fibrosus anchorage is severed by cutting around the base of the herniation tract just outside the inner edge of the annular fibrosus perforation. Once the herniation base is free, the fragment(s) is pulled out.

Endoscopic Decompression

When nerve root compression occurs in the lateral recess and the intervertebral foramen, endoscopic decompression is feasible without causing segmental instability [Figs. 12.5(b), 12.5(d)]. The foramen floor is removed by performing partial annulectomy. In addition, the bony deep surface of the facet is laser-ablated, thereby releasing hypertrophic ligamentum flavum attached to the anterior edge of the superior articular process. A 5-mm trephine can be used to more aggressively decompress the undersurface of the superior articular process as well as the tip of the facet to expose the undersurface of the inferior facet. Newly developed high-speed diamond burrs and shaver-based burrs can smooth out the bony surface. Specially developed kerrisons can also be utilized by surgeons experienced in foraminoplasty. The Holmium YAG laser is an effective tool that can be used to remove bone and ligamentous tissue as well. The end point is the identification of fat in the foramen or the visualization of a pulsating traversing and exiting nerve.

Pearls and Pitfalls

- The patient is positioned to obtain true AP and lateral views prior to needle placement; this will avoid

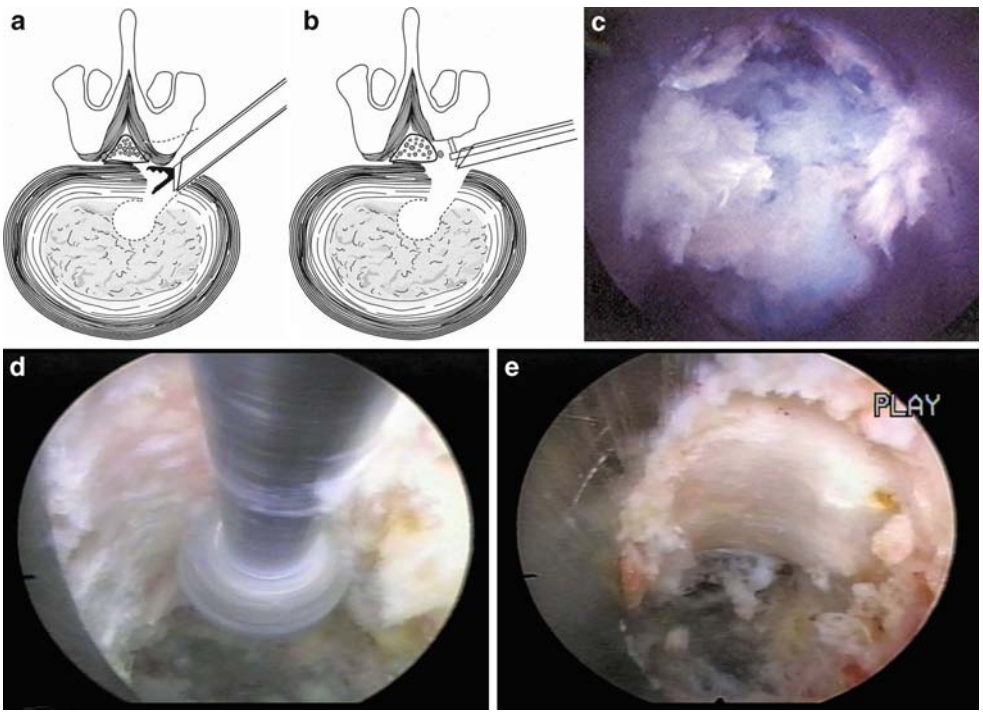

Fig. 12.5 (**a, b**) The biting forceps and the side-firing Holmium yttrium-aluminum-garnet laser are used to release the annular collar. Then the extruded nuclear fragments can be pulled through the widened annular window and into the working cavity. (**b**) Access to the base of the disc fragment can be challenging at the L5-S1 level or in medial herniations, as the superior articular process may block access. Partial resection of this bony block with an endoscopic burr facilitates access toward the medial canal. (**a, b**) Partial annulectomy and partial resection of the superior articular process also serve to decompress the lateral recess and neuroforamen. (**c**) Endoscopic illustration of the medialized annular ligament, exposing the herniation extruded past the posterior annulus. (**d**) Endoscopic decompression of the superior facet with a diamond burr. (**e**) The initial pass of the diamond burr creates a domed cavity into the base of the superior facet of the inferior vertebra. The decompression is continued under endoscopic visualization, using the side of the cannula to retract and protect the exiting nerve. After reaching the exiting nerve, further decompression can be performed, following the exiting nerve to the axilla between the exiting and traversing nerves, thus decompressing the subarticular spinal segment on the side of the decompression. The caudal edge of the exiting nerve is seen at 5 o'clock. [Parts (a) and (b) reprinted with permission from Yeung and Tsou [2], Lippincott Williams & Wilkins.©]

radiographic parallax error and malpositioning of the needle, cannula, and endoscope. Fluoroscopy and ideally dual C-arms should be used to confirm location if there is *any uncertainty* about anatomy or location during endoscopy.

- It is recommended that the patient be *awake and alert* until the endoscope is within the disc space to avoid nerve injury. Avoiding excessive sedation prior to this point in the procedure is crucial, especially during needle insertion and dilator and cannula passage. We recommend against the use of a general anesthetic such as Propofol.
- *The initial needle trajectory and placement are* es*sential*because they will ultimately determine the endoscopic field of view. A flat trajectory is often desired but is blocked by a hypertrophic superior articular process. This can be removed after the endoscope is inserted using trephines and the endoscopic laser. This step also opens the neuroforamen by releasing the lateral attachment of the ligamentum flavum.
- Start the endoscopy using the inside-out technique, accessing the intervertebral disc, which is always safe! This technique is especially important during the initial learning curve. Beginning the endoscopy before reaching the disc annulus can make the recognition of foraminal anatomy more difficult and can increase the likelihood of nerve root injury except in special situations where the patient's anatomy and/or the pathoanatomy justify an alternate technique. Examples of specific situations that require an "outside-in" technique are removal of the lateral facet to get into L5-S1 or a large far-lateral disc sitting on the exiting nerve root and pushing it into the foramen.
- The most difficult herniations are peri-central, large, hard disc extrusions such as a 1-cm disc

herniation with an annular fragment away from the annular window. The retrieval of such herniations may require the use of an additional endoscope from the contralateral side and the use of larger articulating graspers to pull the stalk of the disc fragment back down into the surgical cavity. Large, extruded, sequestered herniations may call for an outside-in technique, which is made easier with a lateral facetectomy being performed first. The endoscopic surgeon must be familiar with these advanced techniques to take on uncontained herniations.

Clinical Outcomes

Kambin and co-workers performed a prospective, randomized study of 60 patients with a single-level posterolateral herniation of a lumbar disc caudal to the first lumbar vertebra [1]. Patients were randomized to group 1, which underwent open laminotomy and discectomy, and group 2, which underwent transforaminal endoscopic discectomy.

Group 1 had 93% satisfactory outcome and group 2 had 97% satisfactory outcome. An excellent or good result is considered a satisfactory outcome. The outcome was considered to be excellent if the radicular symptoms had ceased, the tension signs had become negative, the patient had returned to his or her previous occupation or to normal activity, and the patient expressed satisfaction with the result of the operative procedure. The outcome was considered to be good if the criteria just mentioned were met but the patient had residual back pain and had to modify his or her occupation. It should be noted that this outcomes assessment tool has not yet been validated.

The time to return to work was 49 days for group 1 and 27 days for group 2. In addition, group 1 used narcotics in greater quantities and for a longer duration postoperatively. Group 1 used narcotics for an average of 25 days, while group 2 used narcotics for an average of 7 days. Although the time to return to work and narcotics use appear to favor the endoscopic discectomy group, the statistical significance of the differences was not determined in this study.

Yeung and Tsou reported a retrospective review of their series of 307 consecutive cases of posterolateral endoscopic excision for lumbar disc herniation [2]. At an average follow-up of 19 months, 81.4% of the whole group was found to have an excellent or good result. Patients with work-related or personal injury claims were not excluded from the study. A subgroup of 105 patients (34%) with pending litigations was found to have a reduced rate of excellent/good results of 61.9%. It is not clear whether the litigation subgroup was similar to the primary group in terms of type of disc herniation, duration of symptoms, complication rate, and reoperation rate.

Complications included deep infection ($n = 2$, 0.65%), thrombophlebitis ($n = 2$, 0.65%), dysesthesia ($n = 6$, 1.9%), and dural tear ($n = 1$, 0.3%). The patients with deep infection ($n = 2$) and dural tear ($n = 1$) required reoperation. A total of 13 (4%) patients underwent reoperations. Other reasons for reoperation included congenital short pedicles ($n = 3$), foraminal/lateral recess stenosis ($n = 3$), recurrent herniation ($n = 2$), and missed fragments ($n = 2$).

Ahn et al. reported the results of posterolateral endoscopic discectomy for recurrent lumbar disc herniations [3]. Forty-three consecutive patients with recurrent disc herniation at the same level after a previous conventional open discectomy with an intervening pain-free interval of more than six months underwent percutaneous, endoscopic, laser-assisted disc excisions. Surgical outcomes were assessed using the MacNab criteria and Visual Analog Scale (VAS). Based on the MacNab criteria, excellent or good outcomes were noted in 81.4% of patients. It should be noted that the rate of excellent/good outcomes for recurrent disc herniations was equivalent to that obtained by Yeung and Tsou for primary disc herniations. Risk factors for poor outcome included age > 40 years old, symptoms > 3 months, and the presence of lateral recess stenosis.

More recently, Choi et al. reported the results of an interlaminar endoscopic discectomy technique for L5-S1 disc herniations [4]. Sixty-seven patients underwent the procedure, but two patients required a conversion to open procedure. The remaining 65 cases were evaluated with a minimum of 1.5 years of follow-up and were found to have 90.8% excellent/good results using the MacNab criteria. Complications occurred in 18.5% and included dural injury ($n = 2$), transient dysesthesia ($n = 9$), and recurrence ($n = 1$).

Other applications of the posterolateral endoscopic technique have also been described. Knight et al. described posterolateral endoscopic foraminal decompression in the management of symptomatic isthmic spondylolisthesis [5]. Patients with at least a one-year history of disabling low back and buttock pain with or without referred pain, unresponsive to conservative treatment of at least six months, were included in the study. It should be noted that all except one patient in the study had some degree of radicular leg pain. Endoscopic foraminal decompression with laser-assisted bone and soft tissue ablation was performed in 12 males and 12 females with grades I–III isthmic spondylolisthesis. Excellent/good outcomes were noted in 79% of patients as indicated

by at least a 50% change in Oswestry Disability Index scores. No slip progression was detected postoperatively. It should be noted that only one patient with grade III spondylolisthesis was included in this study, and no conclusion can be made regarding the efficacy of this technique in the management of symptomatic grade III spondylolisthesis.

A prospective evaluation of endoscopic discectomy in 30 consecutive patients with posterolateral or far-lateral lumbar disc herniations was performed [6]. All patients were treated by a single surgeon (CWK). Using the MacNab criteria, we observed 73.2% good/excellent results for the group overall. When the group was divided into two subgroups, we observed 60% good/excellent results in the first 15 patients to undergo the procedure and 87.7% good/excellent results in the second 15 patients to undergo the procedure. This difference in outcome between the two groups likely represents the steep learning curve associated with endoscopic discectomy.

Discussion

The potential benefits of endoscopic microdiscectomy include the absence of epidural fibrosis and tethering of nerve roots, the preservation of intact epidural venous systems, which prevents postoperative venous stasis and chronic nerve root edema, and, finally, the minimal operative trauma to myoligamentous structures. Studies demonstrate that endoscopic discectomy can be performed safely, with acceptable complication rates (Table 12.1). Results are comparable to traditional open discectomy for soft, nonextruded posterolateral disc herniations. Results are superior with extaforaminal disc herniations in experienced hands. Experienced endoscopic surgeons are able to remove sequestered herniations with less surgical morbidity. In addition, the theoretical benefits of endoscopic discectomy are supported by the reduced use of narcotics and a faster return to work postoperatively. The minimal bony resection required by this technique also potentially reduces the likelihood of surgically induced spinal instability. Endoscopic decompression in symptomatic unilateral radicular spondylolisthesis can be successful without postoperative slip progression [5]. Other studies investigating interlaminar approaches and recurrent disc herniations demonstrate ongoing efforts to improve and broaden the indications for the endoscopic technique.

Endoscopic discectomy is technically challenging. Safe and effective access is limited to a narrow channel, and a herniated fragment is accessible only when the operating instrument is placed in the optimal trajectory. As a result, there remains a long and shallow rather than steep learning curve that requires repetition and the recognition of the foraminal anatomy. The advent of special tools such as bipolar radiofrequency ablation, endoscopic burrs, and articulating graspers small enough to pass through the endoscopic working channel improve access to a wider variety of disc fragments. The advent of an interlaminar approach may also further improve the endoscopic technique. In summary, endoscopic discectomy is an attractive approach for the surgical management of lumbar disc herniations. For simple posterolateral or far-lateral disc herniations, endoscopic discectomy produces results at least equivalent to open discectomy while potentially allowing a faster postoperative recovery. Further improvements in instrumentation and refinements in technique will improve surgical access and decrease the learning curve of this promising technique.

Table 12.1 Complications of endoscopic discectomy

Complication	Rate (%)
Transient dysesthesias	1.9–14
Dural tear	0.3–3
Recurrent herniation	1.5
Deep infection	0.65
Thrombophlebitis	0.65

Data from Yeung and Tsou [2] and Choi et al. [4].

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Discectomy and Laminectomy

13

Burak M. Ozgur, Scott C. Berta, and Andrew D. Nguyen

Introduction

Methods of discectomy and lumbar decompression continue to evolve in efforts to perform a surgical decompression. A direct decompression simply requires an operative corridor in which to access the spinal canal. We can study the same approach as some of the latest fusion techniques, including approaches from the anterior, posterior, lateral, and posterolateral. The transforaminal interbody lumbar fusion (TLIF) method developed by Harms [1] is a modification of the posterior lumbar interbody fusion (PLIF) method. The procedure varies primarily in the access to the spine, being a unilateral, posterolateral approach to the spine [2]. This is important to understand because it is an approach that can be used for various surgical goals, including discectomy, laminectomy, and interbody fusion.

Current approaches to lumbar discectomy and techniques in interbody fusion have been greatly influenced by recent advances in minimally invasive spine surgery [3–10]. One minimally invasive tubular system in existence is the METRx system (Sofamor Danek). Another minimally invasive system is the nontubular MaXcess (NuVasive) system, which we describe in this manuscript. It allows rapid, unilateral access to the lumbar spine via a percutaneous route while minimizing the amount of operative soft tissue trauma. These systems are designed to maximize surgical access while minimizing disruption of the musculature. They enable the use of standard instruments to perform conventional surgery and allow direct visualization without requiring special equipment. Additionally, an illuminated operative corridor aids by providing direct visualization with superior lighting.

Indications

The minimally invasive posterolateral approach is proving to be extremely versatile in its deliverance of a surgical corridor. It is being used for lumbar decompression, hemilaminotomy/discectomy, laminectomy, formaminotomy, and interbody fusion. Indications are the same for a routine lumbar decompressive laminectomy/foraminotomy for lumbar stenosis, foraminal stenosis, or lateral recess stenosis.

Description of System Components

Any minimally invasive tubular retractor system can be used for this purpose. The general techniques are all the same. They typically involve the use of successive dilating tubes following incision planning and fluoroscopic targeting (Figs. 13.1, 13.2, 13.3, 13.4 and 13.5). An articulating arm is assembled and secured to the operating table. The tubular retractor provides the actual surgical corridor. Various lengths of retractor blades are available depending on the depth of the wound. The light cable is attached to the access driver for illumination.

Operative Technique

Preparation and Positioning

The patient is placed prone on an operating table that will accommodate fluoroscopy (Fig. 13.1). Generally, we prefer to use a Wilson frame on a Jackson table. The Wilson

Burak M. Ozgur (✉)
Director of Minimally Invasive Spine Surgery, Assistant Professor of Neurosurgery, Department of Neurosurgery, Cedars-Sinai Medical Center, Los Angeles, CA 90048, USA
e-mail: bozgur@gmail.com

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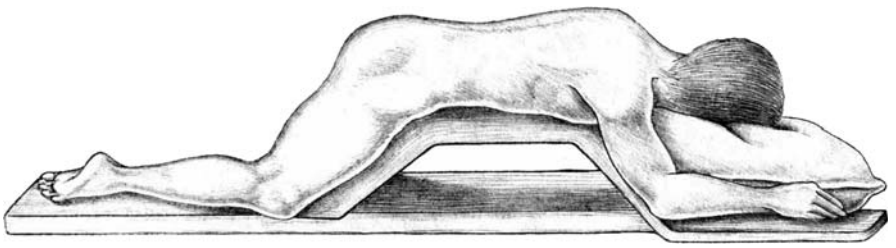

Fig. 13.1 Positioning the patient prone on flexion device (Wilson frame). (From Ozgur et al. [11]. Reprinted with kind permission of Springer Science + Business Media and reproduced with permission of NuVasive, Inc.)

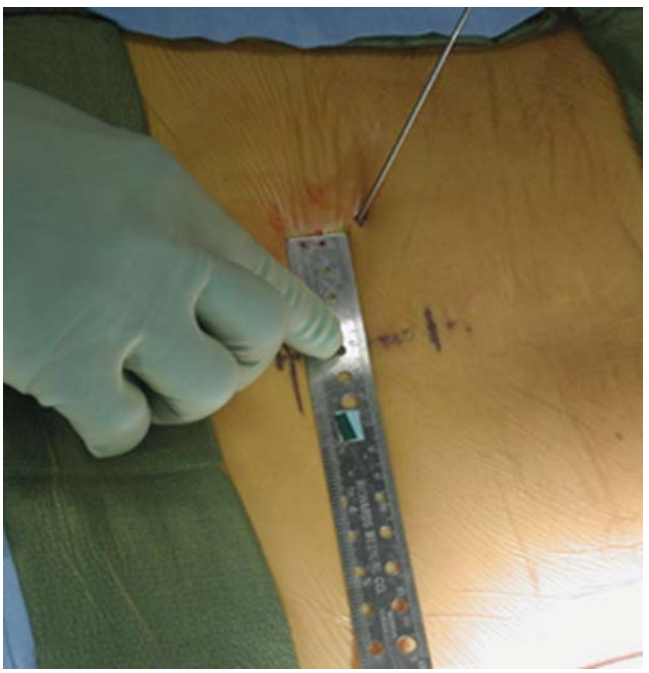

Fig. 13.2 Incision planning

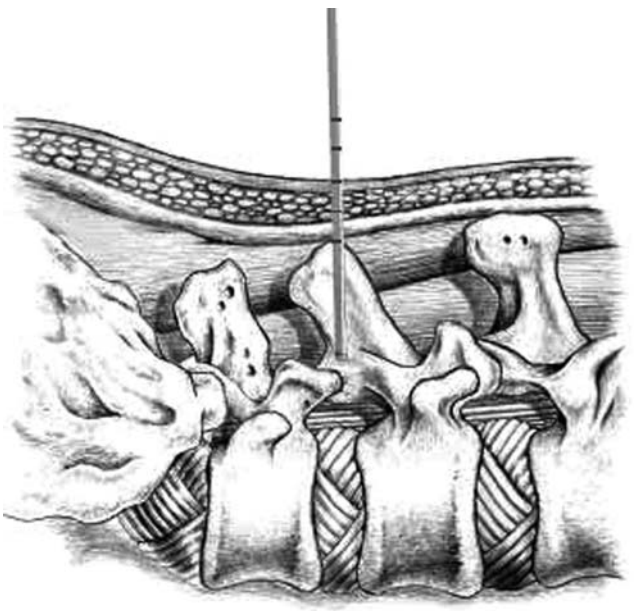

Fig. 13.3 First dilating tube targeting (lateral view). (Reproduced with permission of NuVasive, Inc.)

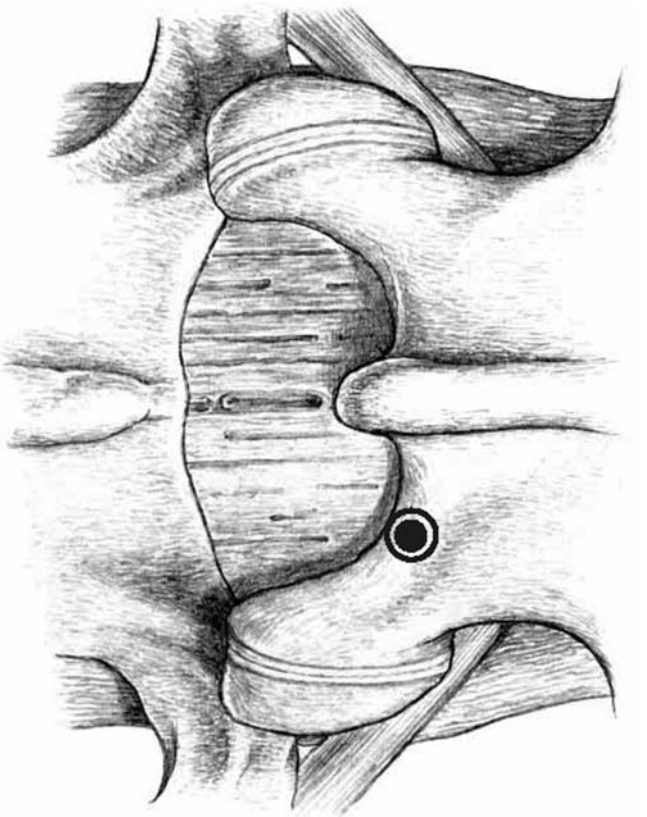

Fig. 13.4 First dilating tube targeting (AP view). (From Ozgur et al. [11]. Reprinted with kind permission of Springer Science + Business Media and reproduced with permission of NuVasive, Inc.)

frame provides lumbar kyphosis to assist in the operative decompression. The Jackson table simply enables fluoroscopic imaging ease. Ensure that a bedrail exists on the contralateral side to the surgeon's position. The patient is then prepped and draped in the usual fashion.

Surgical Procedure

Fluoroscopy in the AP and lateral views is used to locate the affected level. Palpate the spinous process to define the midline. Move approximately one finger-breadth

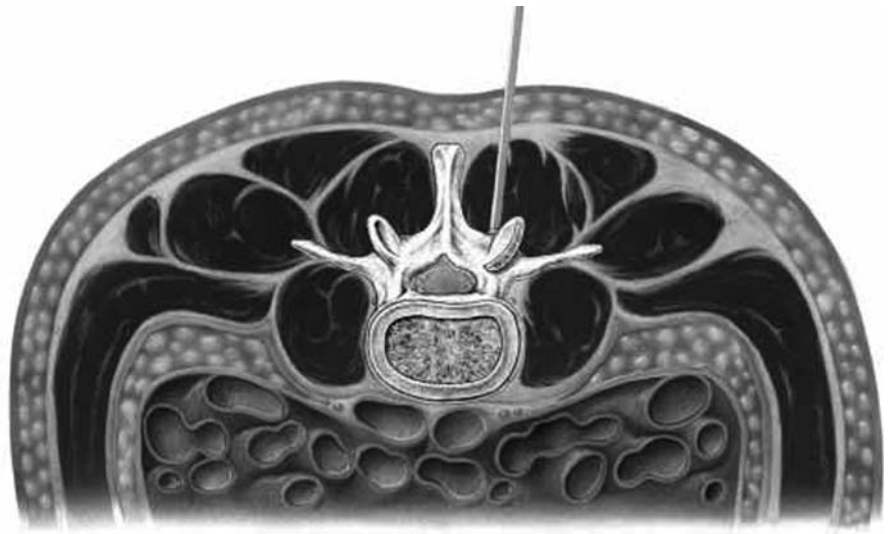

Fig. 13.5 First dilating tube targeting (axial view). (From Ozgur et al. [11]. Reprinted with kind permission of Springer Science + Business Media and reproduced with permission of NuVasive, Inc.)

(depending on the individual patient's anatomy and intended procedure) laterally off midline to mark the incision point on the skin at the level of the affected disc space. Insert the first/narrowest dilating tube at this point, aiming and palpating for the inferior edge of the lamina (Figs. 13.3 and 13.4). Following fluoroscopic verification of placement, a #11 blade is use to make an approximately 2-cm incision (the size depending on the surgical plan and needed exposure). The depth of the incision should penetrate the fascia to easily accommodate the dilators. Successively increasing dilating tubes are now inserted with intermittent fluoroscopy to verify the position and trajectory. Care should always be taken to minimize the chance of penetrating through the interlaminar space. Note the depth of the last dilator, and attach the respective retractor blade to the retractor. Then insert the retractor over the outer edges of the last dilator tube down to the laminar exposure (Fig. 13.6). Affix the articulating arm to the contralateral bedrail and attach the opposite end of the arm to the tubular retractor. While holding the retractor in position, lock the articulating arm by tightening both large T-handles clockwise: first the side handle, and then the back-end handle. Attach the light cables to a xenon light source distally and to the retractor proximally; alternatively, at this point, the microscope may be brought into the field for microsurgical dissection. Bovie electrocautery may be used to remove muscle/soft tissue from the operative corridor.

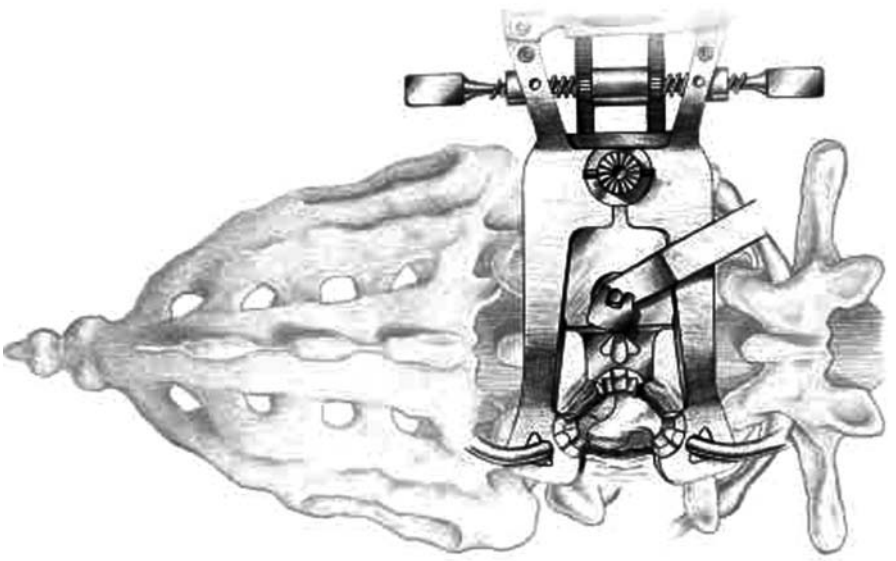

Fig. 13.6 Retractor placement. (Reproduced with permission of NuVasive, Inc.)

Now the positioning and angle of the field can be adjusted to facilitate the desired exposure, whether it is to begin more laterally and work one's way medially, or vice versa. It is worthwhile to note that contralateral laminotomy, laminectomy, and foraminotomy can be performed with the same single incision. The retractor can be angled in any direction in order to facilitate the surgical plan. For example, we angle more medially when performing a contralateral decompression, whereas we angle our view more laterally when preparing for a TLIF.

At this point, one has practically the same exposure as with a traditional open technique. A lateral fluoroscopic image demonstrates the position and trajectory of the retractor for access toward the disc space (Fig. 13.7). The inferior lamina edge can be dissected to free the ligamentum flavum (Fig. 13.8). An operative corridor exposes the thecal sac and traversing nerve root medially and the bony landmarks of the laminotomy cranially and caudally. With minimal retraction of the nerve root, the interbody space/disc can be identified. Figure 13.9 demonstrates that a discectomy can be performed through this approach. By angling the retractor medially, one can appreciate the versatility of this approach in visualizing and facilitating the decompression of the central canal and contralateral lateral recess as well as the foramina. Figures 13.10 and 13.11 demonstrate the trajectory and technique as well as an intraoperative photo

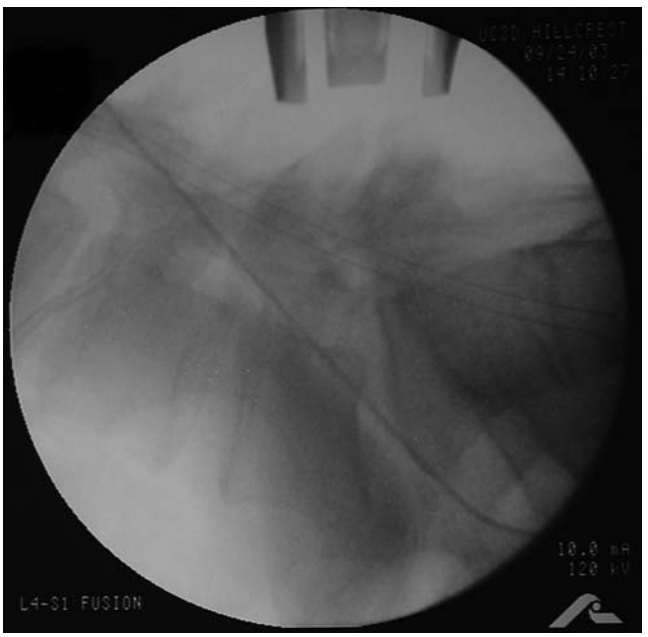

Fig. 13.7 Lateral fluoroscopic image of retractor positioning. (From Ozgur et al. [11]. Reprinted with kind permission of Springer Science + Business Media and reproduced with permission of NuVasive, Inc.)

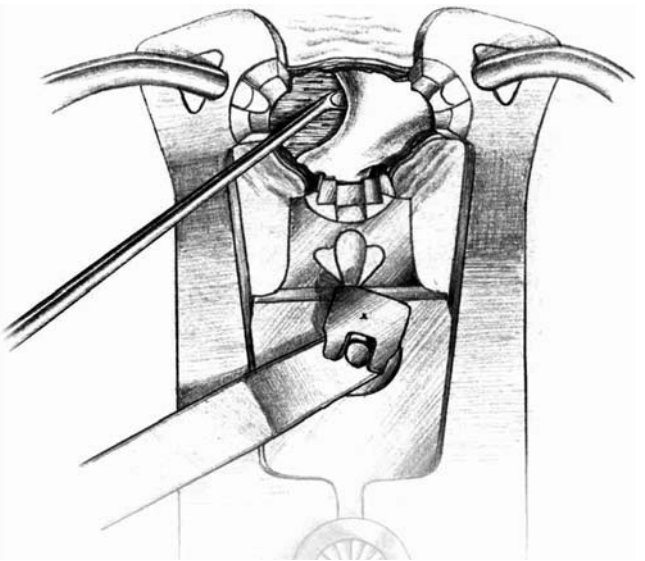

Fig. 13.8 Illustration of curettage of inferior edge of lamina. (From Ozgur et al. [11]. Reprinted with kind permission of Springer Science + Business Media and reproduced with permission of NuVasive, Inc.)

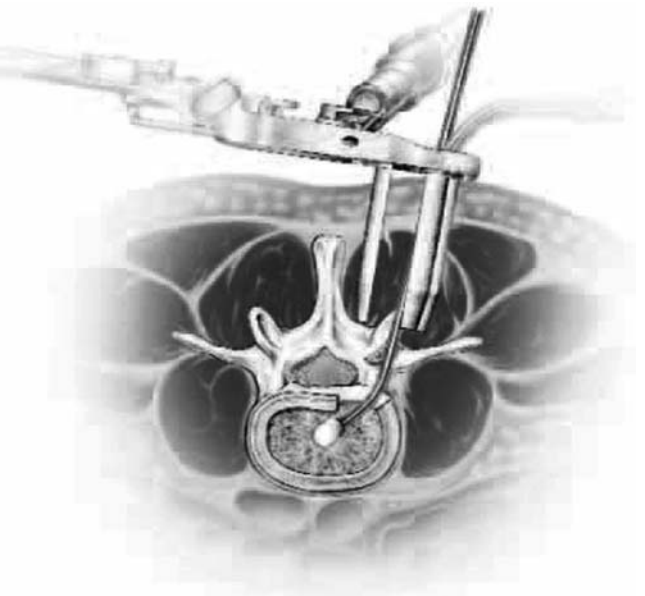

Fig. 13.9 Illustration of discectomy through retractor. (From Ozgur et al. [11]. Reprinted with kind permission of Springer Science + Business Media and reproduced with permission of NuVasive, Inc.)

of the procedure. The structures can be undercut in order to preserve soft tissue and the ligamentous integrity of the posterior tension band. Figure 13.12 demonstrates a postoperative CT scan showing a central and bilateral decompression from a unilateral minimally invasive approach. Due to the fact that no special instruments are required

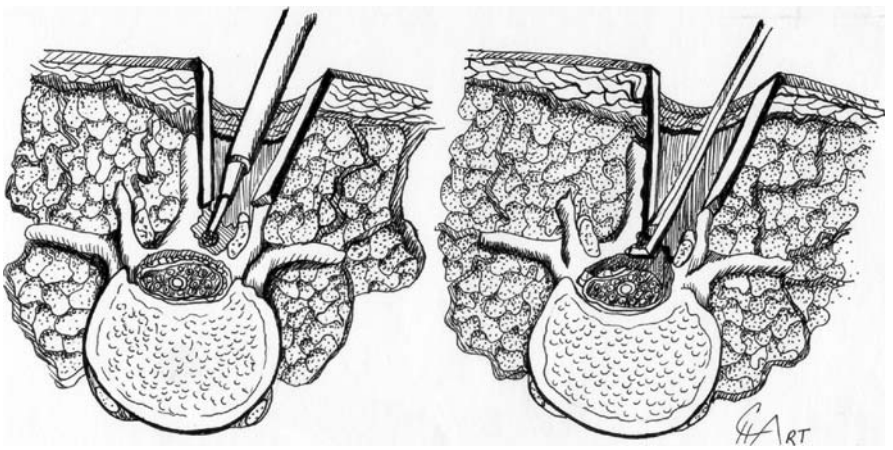

Fig. 13.10 Schematic and intraoperative photo of laminoplasty technique. (From Mayer [12]. Reprinted with kind permission from Springer Science + Business Media)

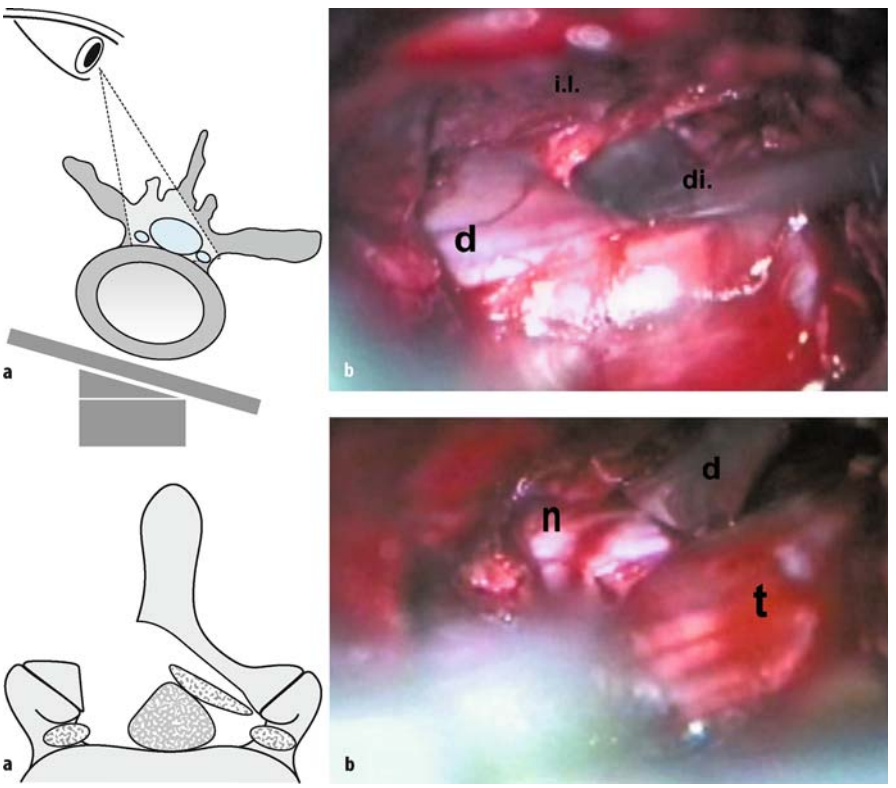

Fig. 13.11 Schematic and intraoperative photo of laminoplasty technique. (From Mayer [12]. Reprinted with kind permission from Springer Science + Business Media)

using this exposure, this application has few limitations. One does not have to use endoscopic instruments through this system.

Complications

Complications related to this exposure are rare. There are certainly risks inherent to performing laminectomies, foraminotomies, and discectomies. However, the risks of performing this exposure are not much different than the apparent risks with any other exposure. Classical bleeding and infection risks remain virtually the same. In fact, this minimally invasive exposure appears to have less morbidity involved, given the off-midline intramuscular approach rather than stripping off all the soft tissue during a typical open midline approach. The inherent risks involve literally getting lost in the minimally invasive anatomy. Certainly, not knowing where one is anatomically can cause trouble. Additionally, a minimally invasive exposure can make it more difficult to correct

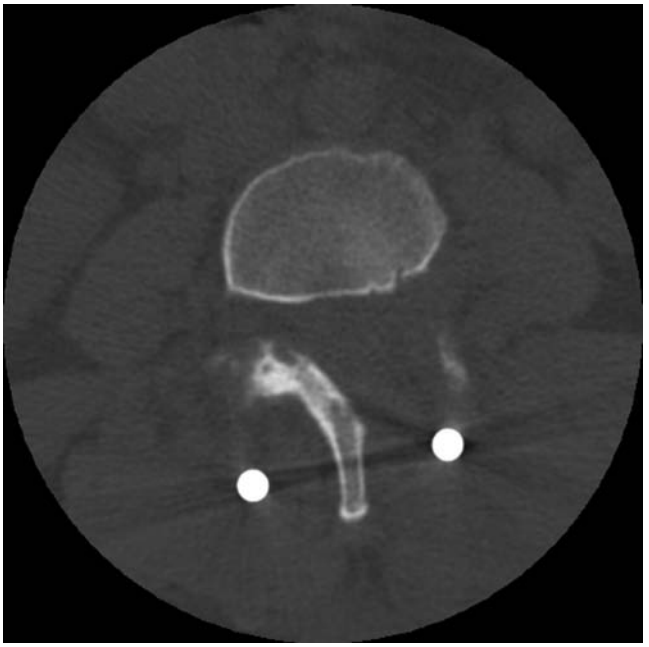

Fig. 13.12 Postoperative CT scan demonstrating bilateral decompression from a unilateral approach

complications such as CSF leak and extensive bleeding. Although since there is nearly no "dead space" following the procedure and the soft tissues fall/close back into anatomical position to close the operative corridor, morbidity is greatly reduced. However, as with any new procedure, there are a learning curve as well as an education in morbidity avoidance. The key seems to be related to the initial retractor placement. If this is done well, then the operative corridor will be ideal and the rest of the case will usually go well. Therefore, providing extra time and attention in the beginning steps will prove to be a good investment.

Discussion

This minimally invasive system for implementing discectomy is proving to be a good tool in a spine surgeon's armamentarium for the surgical correction of spinal disorders. It's a relatively straightforward system providing an excellent operative corridor for a variety of posterolateral spinal procedures, including laminectomy, hemilaminotomy/discectomy, foraminotomy, and PLIF/TLIF. The most important considerations in this approach are whether or not the patient requires a direct decompression and has spinal instability.

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Combining Minimally Invasive Techniques for Treating Multilevel Disease as Well as Adult Degenerative Scoliosis

14

Burak M. Ozgur and Lissa C. Baird

Introduction

With increasing life expectancy and the steadily increasing population of aging adults in the developed world, degenerative diseases are becoming increasingly common to the clinician. Knowing how to manage such conditions with optimal therapeutic benefit, minimal suffering, and minimal costs is necessary for the success of a health-care system. Degenerative disease of the spine in elderly patients is common. In 1.4–12% of the adult population, spinal column degeneration results in a condition known as adult degenerative scoliosis [1–3]. The average age of presentation is in the seventh decade of life, with progressive degeneration.

Degenerative spine disease can result in a deformity of the lumbar spine, specifically in patients older than 65 years of age. Asymmetric intervertebral disc degeneration, osteoporosis, and compression fractures of the lumbar spine can contribute to degenerative scoliosis. These patients can present with various symptoms, including pain, which is the most common complaint. These patients' pain is attributed to several causes associated with the degenerative curve. Abnormal forces distributed along the posterior elements of the spine and corresponding paraspinal muscle attachments on the convex side of the degenerated curve can result in painful muscle spasm. The concave side of the degenerative curve causes compressive forces on exiting nerve roots and ebernation of endplates and facet joints, leading to further neural foraminal narrowing. Adult degenerative scoliosis has been known to exist for several decades. Only 25 years ago, due to the advanced age of patients presenting with this condition, they were considered risky candidates for major spine surgery; until recently, only a few surgeons operated on this condition [2]. The surgical correction of adult scoliosis is common practice today due to progress in modern anesthesia for spine surgery as well as surgical techniques and technology.

Burak M. Ozgur (✉)
Director of Minimally Invasive Spine Surgery, Assistant Professor of Neurosurgery, Department of Neurosurgery, Cedars-Sinai Medical Center, Los Angeles, CA 90048, USA
e-mail: bozgur@gmail.com

Clinical Presentation

Back pain is the most common complaint of patients with adult degenerative scoliosis; however, radicular symptoms and neurogenic claudication are frequent [2–4]. Deformity is typically seen in the lumbar or thoracolumbar region, with characteristically small Cobb angles when compared to adolescent idiopathic scoliosis. Decompensation in the coronal plane is usually toward a lumbar or thoracolumbar apex [2–4]. Sagittal imbalance, with the patient leaning forward, is often seen with flexed hips and knees in an attempt to compensate for the loss of lumbar lordosis or even frank kyphosis [4]. Neurologic deficits are seen less commonly. Cardiopulmonary compromise seen in adolescent idiopathic scoliosis with large Cobb angles is not typically seen in degenerative scoliosis due to smaller curves [4]. Objective findings are rare [2, 3].

Diagnostic Evaluation

Plain Radiography

Full-length radiographs of the spine with AP and lateral views are necessary for a complete evaluation of the spine. Signs of spine degeneration on radiographs include hypertrophic joint facets, narrow disc spaces, and the presence of osteophytes. Static films show rotation, lateral listhesis, spondylolisthesis, and

B.M. Ozgur et al. (eds.), *Minimally Invasive Spine Surgery*, DOI 10.1007/978-0-387-89831-5_14,

retrolisthesis. Dynamic lateral-view flexion and extension radiographs may show a translation of one vertebral body over another. Supine bending films and supine extension films may be rarely indicated for assessing the flexibility of curvature in the coronal and sagittal planes [3]. Radiographic parameters have been shown to correlate with the subjective perception of pain on the Visual Analog Scale [1]. Plain radiography in conjunction with MRI or CT myelogram is vital for preoperative surgical planning.

MRI and CT Myelography

MRI is an excellent tool for assessing the spinal cord, nerve roots, spinal canal, and nerve root foramen. Typical areas of stenosis are L2-3, L3-4, and L4-5. Posterior bulging of intervertebral discs, hypertrophic facets, and hypertrophic ligaments contribute to spinal and foraminal stenosis. CT myelogram is useful for large curves or when there is a significant dynamic component that needs further delineation [4].

Discograms and Facet Blocks

Functional discograms and epidural blocks may be especially useful for evaluation of a pain source. Findings from these studies are important, as they help guide therapeutic approaches. The main advantage of functional anesthetic discograms is in selecting prospective vertebral levels for surgical fusion. The high-pressure injection of saline/dye into the disc space produces concordant pain, and degenerative/disruptive changes may be seen on imaging. Since the pain from degenerative scoliosis arises from multiple levels, discograms and facet blocks can be performed sequentially at multiple levels to identify the most probable pain generator level [3, 5].

Therapeutic Intervention

Nonoperative Management

Nonoperative treatment is the first line in the management of symptoms related to adult degenerative scoliosis and is effective in symptom relief in a large number of patients [6, 7]. Options include NSAIDs, muscle relaxants, narcotic pain medication, muscle exercises, swimming, and occasional gentle traction along with avoidance of activity and manipulations that aggravate the pain [2, 4, 6]. Epidural blocks and selective nerve blocks can be used for short-term palliative relief [7, 8]. Spine bracing and corsets have also been used with varying degrees of relief [2, 4]. The efficacy of nonoperative treatment may depend greatly on the nature and severity of the patient's symptomatic and radiographic presentation. Studies on nonoperative treatment of patients with between one and five years of follow-up suggest that 15–43% of patients will have continued improvement after nonoperative treatment [7]. When nonoperative management strategies fail, operative treatment is indicated.

Operative Management

Surgery is indicated for persistent significant back or radicular pain despite conservative management, as well as for the progression of deformity and for neurologic deficits. The goals of surgical treatment are the decompression of neural elements and the achievement of a stable, balanced spine. Surgical goals are achieved through a combination of neural decompression, curve manipulation, segmental fusion, and instrumentation [3, 4].

The severity and extent of the spinal stenosis and deformity determine the type of operative procedure to be performed.Options include decompression alone, decompression and posterior spinal fusion with instrumentation, decompression with anterior spinal fusion and posterior spinal fusion with instrumentation, and fusion and instrumentation with extension to the sacrum and pelvis [4]. Irwin et al. described significant variations in the treatment approach among surgeons [9]. Orthopedists recommended fusion and instrumentation more often than neurosurgeons for all cases, reaching significance for degenerative scoliosis with stenosis ($p = 0.02$ for both fusion and instrumentation). Younger surgeons were generally more likely to recommend instrumentation than their older peers, reaching significance for multilevel stenosis without deformity or instability and recurrent stenosis following prior laminectomy without deformity or instability ($p = 0.05$ and 0.01, respectively).

The Lateral Transpsoas Approach

The Extreme Lateral Interbody Fusion (XLIF) technique was first presented in 2001 by Pimenta, who has performed more than 100 lateral transpsoas surgeries since 1998 [10]. XLIF is a modification of the retroperitoneal approach to the lumbar spine. The XLIF approach allows for anterior access to the disc space without an approach

surgeon or the complications of an anterior intraabdominal procedure. The equipment used in this procedure is uncomplicated, is conventional, and does not require additional capital expenditure (see Chapter 16).

The Paracoccygeal Transsacral Access to the Lumbosacral Junction for Interbody Fusion and Stabilization

The paracoccygeal transsacral exposure technique represents another option for minimally invasive access to the lumbosacral junction. This approach utilizes instruments to enable fusion and stabilization principles to facilitate primary lumbar fusions or extensions of long fusions across the lumbosacral junction, while it minimizes the soft tissue trauma associated with traditional lumbar fusion through open surgical techniques (see Chapter 9).

Percutaneous Pedicle Screw Placement for Spinal Instrumentation

Percutaneous pedicle screw instrumentation can be performed safely and effectively. The benefits included are reduced tissue dissection and blood loss, preservation of normal anatomical supporting structures of the spine, and quicker recovery. The pedicle offers the strongest site of fixation for spinal instrumentation. Mastering radiographic targeting of the pedicle can be done with a thorough appreciation of the bony anatomy of the spine and those landmarks critical in performing safe and accurate percutaneous pedicle screw placement. In addition, intraoperative percutaneous pedicle screw stimulation seems to reduce approach-related morbidity and is an excellent technique to confirm the adequacy of screw placement (see Chapter 18).

Case Examples

Case 1

A 38-year-old female presented to our office complaining of chronic unrelenting low back pain. Patient demonstrated degenerative disc disease from L3-S1. Chronic attempts at conservative nonoperative management were performed to no avail. The patient opted for surgical intervention. Traditional and minimally invasive options were discussed. The patient underwent a two-level transpsoas approach to anterior lumbar fusion (XLIF) at L3-4 and L4-5 as well as the percutaneous presacral L5-S1 instrumentation and fusion (AxiaLIF), ending with percutaneous pedicle screw instrumentation from L3-S1 with a staggered technique. The thought process of the staggered technique is to leave a free pedicle available at the end of the construct in order to allow additional minimally invasive techniques in the event of adjacent-level disease without requiring a screw/rod removal/revision. The further benefit here is that having performed this minimally invasively with limited soft tissue damage, hopefully there would be a diminished risk for adjacent-level disease. Furthermore, we have only done the staggered percutaneous pedicle screw technique in cases where we had placed a large anterior interbody construct such as XLIF/DLIF cages or a strong AxiaLIF screw but still wanted more stability than a standalone construct. In any case, the patient did very well, was ambulatory postoperative day (POD) 1, and was discharged POD 3. Her postoperative AP and lateral x-rays are demonstrated in Figs. 14.1 and 14.2.

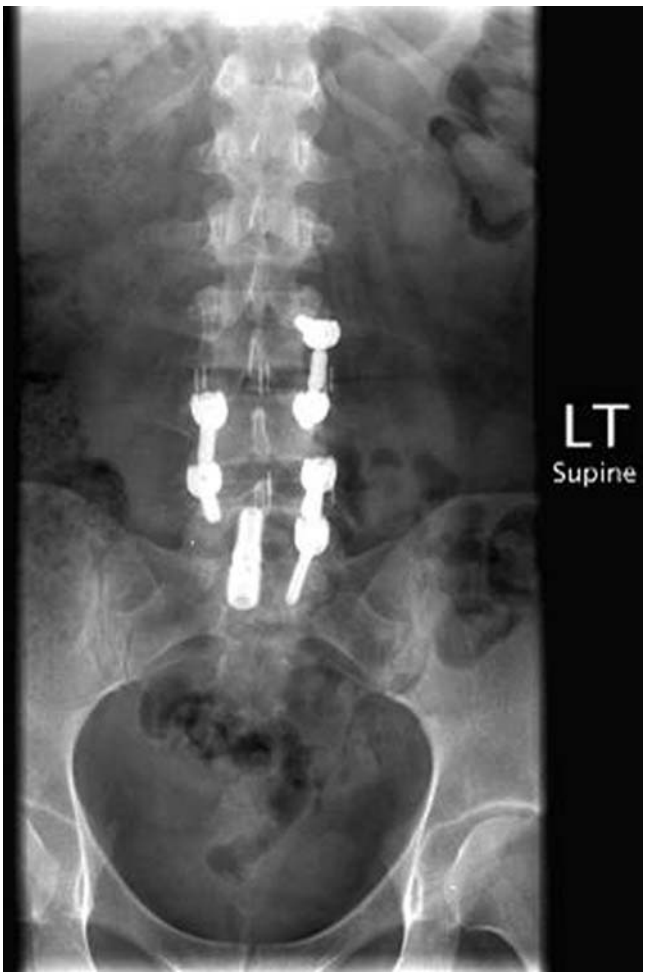

Fig. 14.1 AP X-ray of patient with L3-4-5 XLIF, L5-S1 AxiaLIF, and percutaneous screws

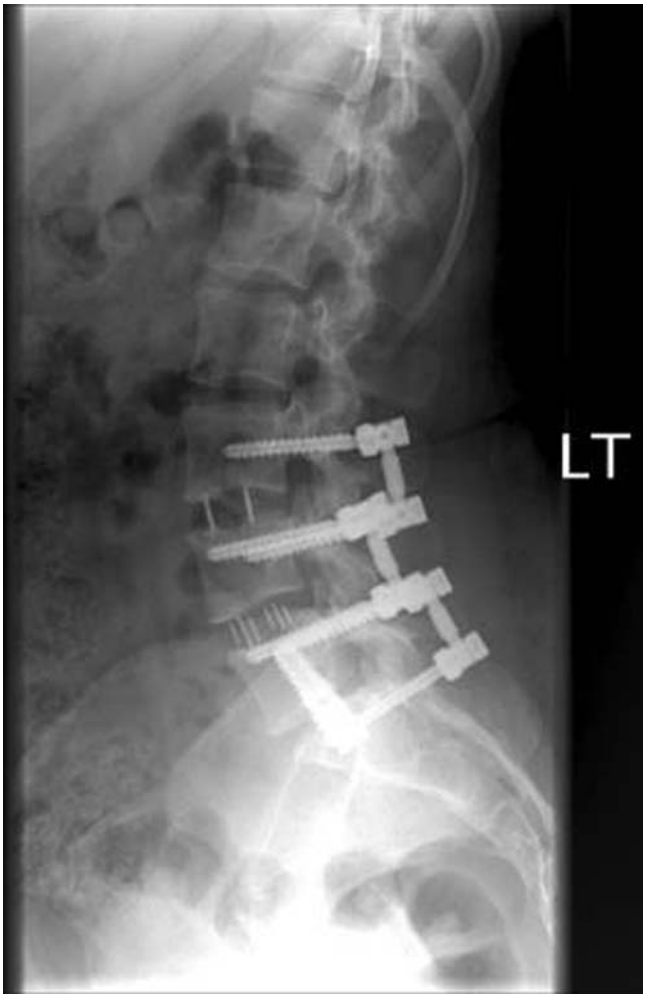

Fig. 14.2 Lateral X-ray of patient with L3-4-5 XLIF, L5-S1 Axia-LIF, and percutaneous screws

Case 2

A 70-year-old woman presented to the spine clinic complaining of chronic low back pain and intermittent leg pain, numbness, and tingling (right leg > left leg). She had adult degenerative scoliosis from T12-L5 and had developed an autofusion at L5-S1. Having failed nonoperative management, we discussed traditional open techniques versus minimally invasive approaches. The patient opted for minimally invasive surgery given all the benefits. We performed a five-level lateral transpsoas approach for anterior lumbar interbody fusion and posterior pedicle screw and rod instrumentation. The patient did very well. Despite being a large patient in excess of 260 lb, and having undergone a five-level instrumented fusion, she was up and out of bed on POD 1. Her preoperative MRI is demonstrated as Fig. 14.3. Her AP and lateral X-rays at the end of the XLIF portion alone are

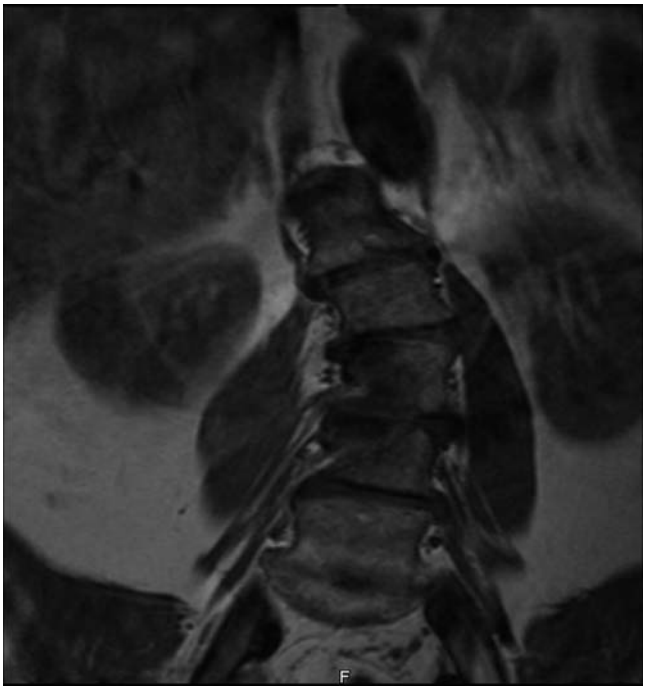

Fig. 14.3 Preoperative MRI of patient with adult degenerative scoliosis

demonstrated in Figs. 14.4 and 14.5, showing a remarkable correction of her scoliosis. Finally, Figs. 14.6 and 14.7 demonstrate the final standing AP and lateral X-rays following the pedicle screw instrumentation. The amount of interbody height restoration and the notable correction of scoliosis from just the lateral interbody work are

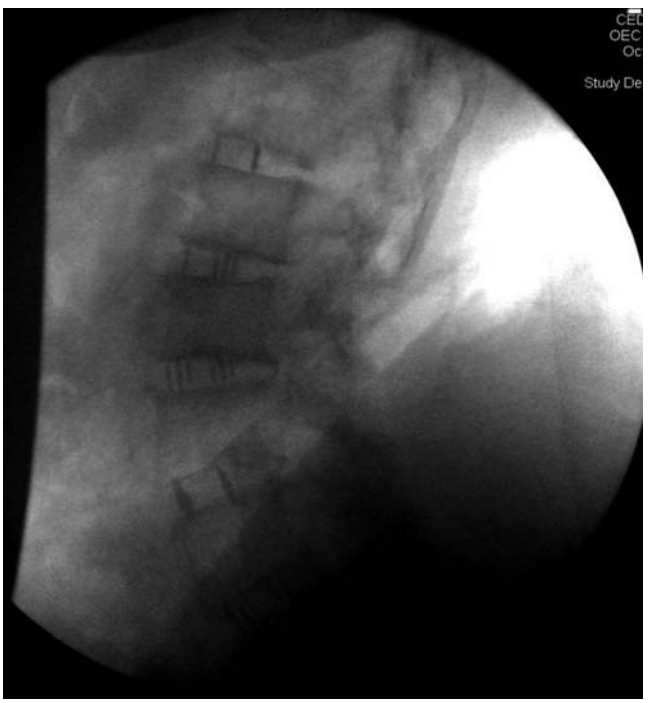

Fig. 14.4 Intraoperative lateral X-ray of patient with five-level XLIF

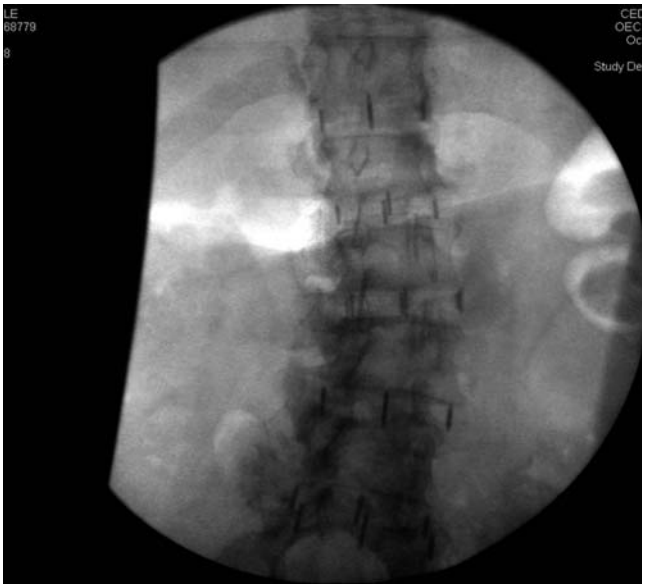

Fig. 14.5 Intraoperative AP X-ray of patient with five-level XLIF

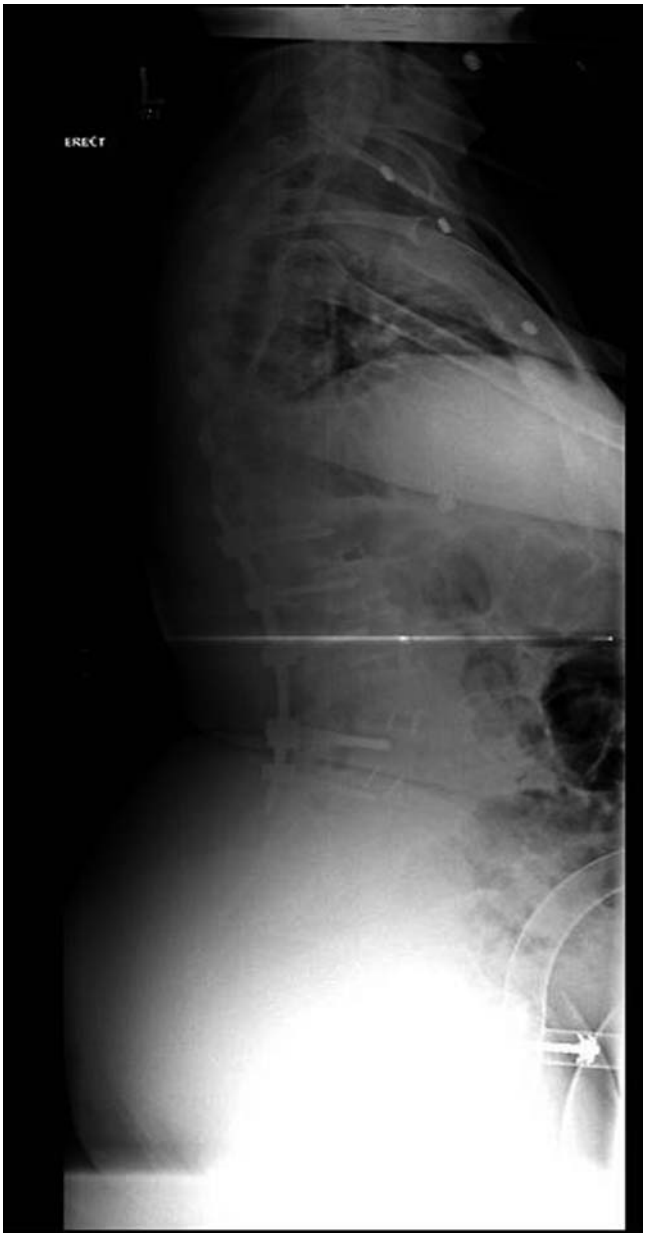

Fig. 14.6 Postoperative lateral X-ray of patient with T10-L5 minimally invasive adult degenerative scoliosis correction

remarkable. It is of note here that it is rather unconventional that this patient has a pedicle screw construct ending on L4 on one side and L5 on the other. However, as commented earlier, a large anterior interbody cage is present in addition to the concept of leaving one L5 pedicle available in the chance that in the future L5-S1 requires surgical intervention.

Discussion

Degenerative disease of the disc space typically affects the anterior column of the lower lumbosacral spine. Many patients presenting with symptomatic degenerative scoliosis are older than 50 years and often have medical comorbidities such as cardiac disease, type 2 diabetes mellitus, and vasculopathy. These patients are more vulnerable to extensive surgical procedures and long operative times. Spinal fusion is commonly performed for the treatment of spinal instability and back pain at the lower lumbar segments. The open anterior and posterior surgical approaches often cause significant muscular injury, ligamentous dissection, and retraction injury to vascular, visceral, and neural structures, causing complications [11, 12]. These approaches can cause short- and long-term increases in pain and functional sequelae.

The XLIF technique is novel in that it can be used to gain access to the lumbar spine via a lateral approach that passes through the retroperitoneal fat and psoas major muscle. When compared with anterior laparoscopic approaches to the lumbar spine, the lateral approach has several advantages. First, a general surgeon is not needed for access. Second, compared with laparoscopic techniques, no steep learning curve exists for these minimally disruptive techniques. All tissue dissection occurs under direct vision, without impairment of depth perception. Third, both approaches eliminate the need to violate or retract the peritoneum or to retract the great vessels. Both approaches avoid many of the known complications of laparoscopic anterior approaches, such as damage to

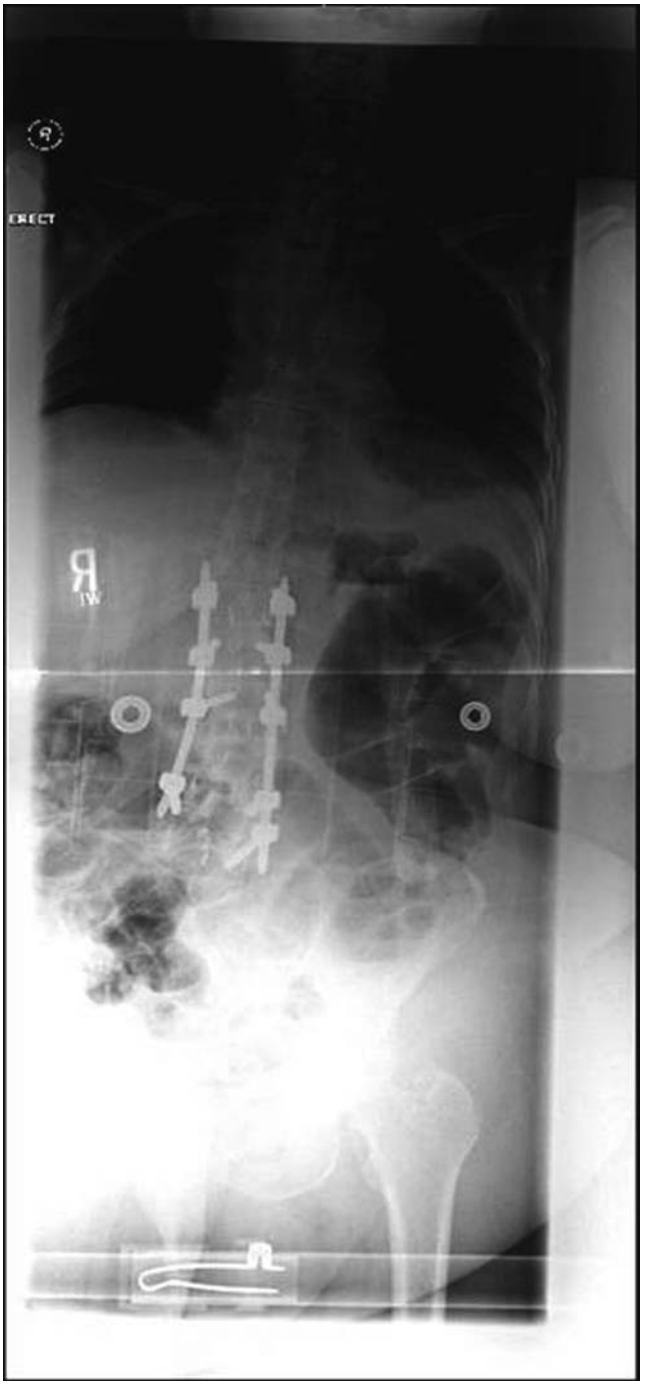

Fig. 14.7 Postoperative AP X-ray of patient with T10-L5 minimally invasive adult degenerative scoliosis correction

the great vessels during mobilization [13, 14] and retrograde ejaculation [15, 16]. Fourth, both require less operative time. Additionally, with a less traumatic approach and shorter operative times, patients recover faster from these procedures, resulting in a decreased hospital stay and less reliance on postoperative therapy and pain medications, which translate into less cost to the patient and the health-care system.

The limitations of the far-lateral approach include injury to nerves of the lumbar plexus and trauma to the psoas major [11]. Use of the NeuroVision EMG monitoring system is critical to the safe application of instruments within the retroperitoneal space and psoas muscle in the XLIF procedure. The procedure needs to be carried out with intraoperative fluoroscopic imaging.

Disc heights were restored and stability was maintained by preserving ligamentous structures and inserting a large interbody implant. This can indirectly improve the foraminal volume and result in a reduction of the radiculopathy. Sagittal balance was maintained or improved by placing the implant in an anterior position. Coronal imbalances were corrected by ensuring full bilateral endplate coverage by the implant.

One must remember that the decompression achieved here is indirect by way of interbody distraction and ligamentotaxis. In other words, a patient with predominant stenosis and neural compression may require a direct decompression through another technique.

Conclusion

The complexity of the clinical manifestation, pathophysiology, imaging findings, and treatment options for adult degenerative scoliosis makes the management of this condition challenging. While nonoperative treatment is adequate in a large number of patients for symptom relief, many patients require operative procedures. Surgical strategies involve a combination of neural decompression, curve manipulation, segmental fusion, and instrumentation and are associated with significant risks in the given age group. The XLIF procedure is a new tool in the armamentarium of the spine surgeon that allows for anterior access to the lower lumbar disc space for interbody distraction and fusion, via a minimally invasive corridor, without an approach surgeon or the potential complications of an anterior approach. The added benefits of the minimally invasive approach to interbody fusion are the decreased blood loss, postoperative pain, and hospital length of stay.

We have found that one can achieve a remarkable correction of spinal deformity, including AP, lateral, and rotatory listhesis, by simply restoring the interbody height. We believe this lends itself to a more “holistic” deformity correction without the need for massive torque forces on pedicles as in traditional scoliosis correction. On selected cases, we perform standalone constructs, while with others, the staggered percutaneous pedicle screw

technique may be best. With a large interbody cage construct in front, a traditional bilateral pedicle screw construct is not always needed.

Furthermore, combining these various techniques allows us to concentrate and offer patients treatment customized to their individual pathology, but performed in a minimally invasive manner.

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Transforaminal Lumbar Interbody Fusion (TLIF)

15

Burak M. Ozgur, Scott C. Berta, and Samuel A. Hughes

Introduction

Methods of spinal arthrodesis continue to evolve in efforts to treat back pain. The latest techniques include approaching from the anterior, posterior, lateral, and posterolateral. The transforaminal interbody lumbar fusion (TLIF) developed by Harms [1] is a modification of the posterior lumbar interbody fusion (PLIF). The procedure varies primarily in the access to the spine, being a unilateral, posterolateral approach to the spine [2]. Simultaneous pedicle screw fixation can be used to achieve anterior column stability.

The TLIF has been shown to be a valuable alternative to the traditional PLIF [3–7]. Advantages of the TLIF over the PLIF are fewer complications [4], the elimination of epidural scarring [1], less intraoperative bleeding [4], and the avoidance of dura and nerve roots [2, 4]. Further, given its unilateral approach, the TLIF offers better preservation of the lumbar spine musculoligamentous complex.

Current approaches to lumbar discectomy and techniques in interbody fusion have been greatly influenced by recent advances in minimally invasive spine surgery [8–15]. One minimally invasive tubular system in existence is the METRx system (Sofamor Danek). Another minimally invasive system is the Atavi (Endius). One nontubular system which we describe further in this chapter is called MaXcess (NuVasive). A variation on the standard TLIF, it allows rapid, unilateral access to the lumbar spine via a percutaneous route while minimizing the amount of operative soft tissue trauma. The MaXcess system is designed to maximize surgical access while minimizing disruption of the musculature. It enables the use of standard instruments to perform conventional surgery and allows direct visualization without requiring special equipment. Additionally, an illuminated operative corridor aids in providing direct visualization with superior lighting.

Indications

The transforaminal approach is proving to be extremely versatile in its deliverance of a surgical corridor. It is being used for lumbar decompression, hemilaminotomy/discectomy, formaminotomy, and interbody fusion. Indications include the need for a direct decompression as well as stabilization and fusion for instability.

Description of System Components

The MaXcess TLIF system (NuVasive, San Diego, CA, USA) enables a surgical corridor for the performance of various surgical procedures. This system includes successive dilating tubes following incision planning and fluoroscopic targeting (Figs. 13.2, 13.3, and 15.1). An articulating arm is assembled and secured to the operating table. The access driver provides the actual surgical corridor. Various lengths of retractor blades are available depending on the depth of the wound. An assortment of shim blade extensions is available for added exposure. The light cable is attached to the access driver for illumination.

Burak M. Ozgur (✉)
Director of Minimally Invasive Spine Surgery, Assistant Professor of Neurosurgery, Department of Neurosurgery, Cedars-Sinai Medical Center, Los Angeles, CA 90048, USA
e-mail: bozgur@gmail.com

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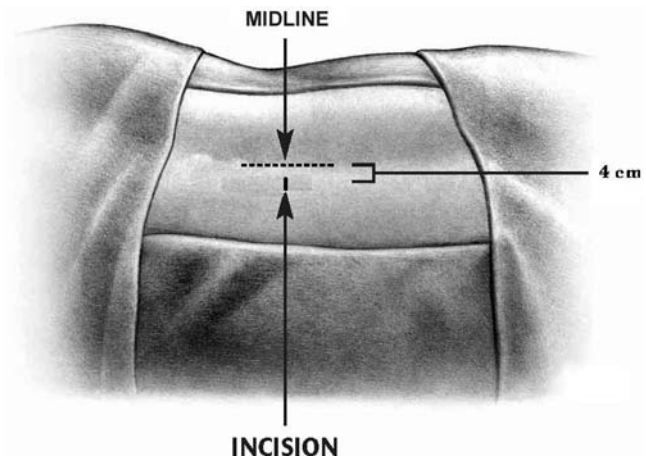

Fig. 15.1 Incision planning. (From Ozgur et al. [16]. Reprinted with kind permission of Springer Science+Business Media and reproduced with permission of NuVasive, Inc.)

Operative Technique

Preparation and Positioning

The patient is placed prone on an operating table that will accommodate fluoroscopy (Fig. 15.2). Ensure that a bedrail exists on the side contralateral to the surgeon's position. The patient is then prepped and draped in the usual fashion.

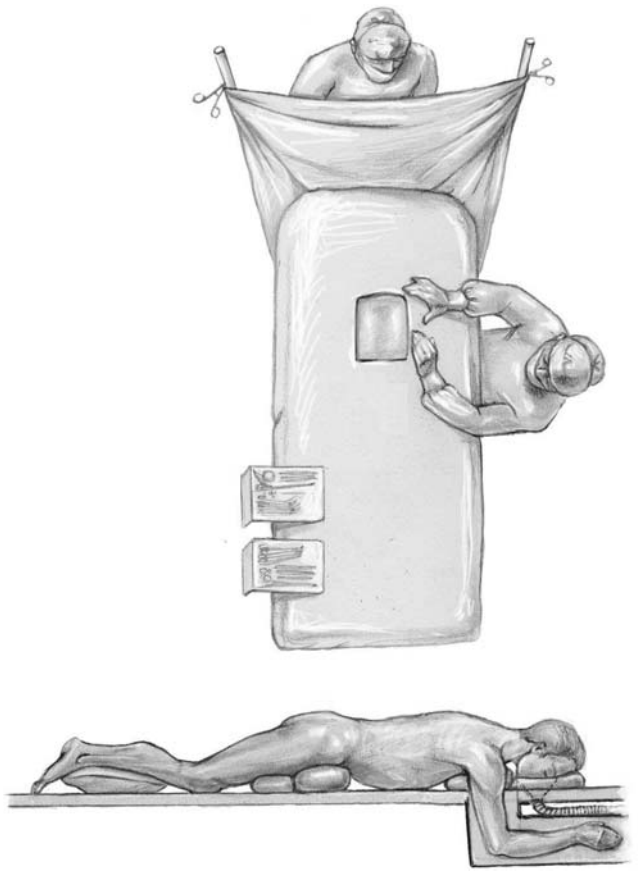

Fig. 15.2 Positioning the patient prone. (Reproduced with permission of NuVasive, Inc.)

Surgical Procedure

Fluoroscopy in the AP and lateral views is used to locate the affected level. Palpate the spinous process to define the midline. Move approximately 2.5–3.5 cm (depending on the individual patient's anatomy and intended procedure) laterally off the midline to mark the incision point on the skin at the level of the affected disc space (Fig. 13.1). Insert the first/narrowest dilating tube at this point, aiming and palpating for the inferior edge of the lamina (Figs. 13.2 and 13.3). Following fluoroscopic verification of placement, a #11 blade is use to make an approximately 2–4-cm incision (the size depends on the surgical plan and the necessary exposure). The depth of the incision should penetrate the fascia to easily accommodate the dilators. Successively increasing dilating tubes are inserted now with intermittent fluoroscopy to verify the position (Fig. 13.3). Care should always be taken to minimize the chance of penetrating the interlaminar space. Note the depth of the last dilator, and attach the respective retractor blade to the access driver. Then insert the access driver over the outer edges of the last dilator tube down to the laminar exposure (Fig. 13.5). Affix the articulating arm to the contralateral bedrail, and attach the opposite end of the arm to the access driver (Fig. 15.3). While holding the access driver in position, lock the articulating arm by tightening both large T-handles clockwise: first the side handle, and then the back-end

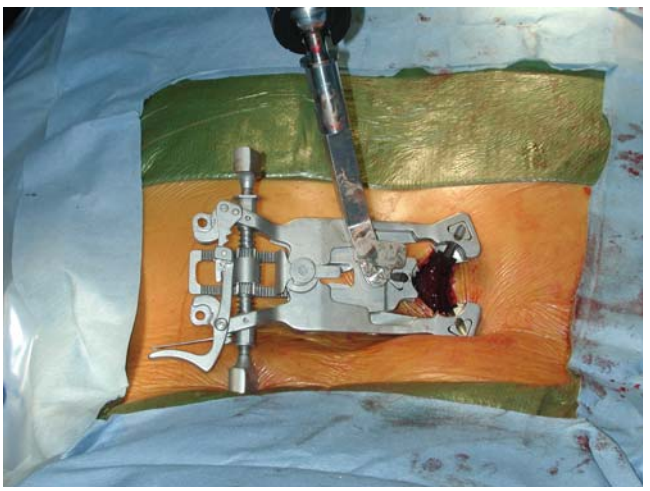

Fig. 15.3 Access driver secured. (From Ozgur et al. [16]. Reprinted with kind permission of Springer Science+Business Media)

handle. Squeeze the handles on the access driver to expand the blades in a cranial/caudal orientation. Now independently retract the lateral blade by turning the knob on the side of the access driver. Attach the light cables to a xenon light source distally and to the access driver proximally (Fig. 15.4). Bovie electrocautery may be used to remove muscle/soft tissue from the operative corridor.

Now the positioning and angle of the field can be adjusted to facilitate the desired exposure, such as beginning more laterally and working one's way medially, or vice versa. It is worthwhile to note that contralateral laminotomy, laminectomy, and foraminotomy can be performed with the same single incision. The retractor can be angled in any direction in order to facilitate the surgical plan. For example, we angle more medially when performing a contralateral decompression, whereas we angle our view more laterally when preparing for a TLIF.

At this point, one has practically the same exposure as that with a traditional open technique. A lateral fluoroscopic image demonstrates the position and trajectory of the retractor for access toward the interbody space (Fig. 13.6). The inferior lamina edge can be dissected to free the ligamentum flavum (Fig. 13.7). An operative corridor exposes the thecal sac and exiting nerve root medially and the bony landmarks of the laminotomy cranially and caudally. With minimal retraction of the nerve root, the interbody space/disc can be identified. Certainly, there are dozens of techniques for performing the discectomy and preparing the interbody endplates for the interbody graft placement (Figs. 13.8, 15.5 and 15.6). Percutaneous pedicle screw instrumentation can be performed to supplement the stabilization (Fig. 15.7). Due to the fact that no special instruments are required using this exposure, there really are not many limitations to the TLIF. One does not have to use endoscopic instruments through this system. Furthermore, although one may use an operative microscope in conjunction with this exposure, it certainly is not required. We found that

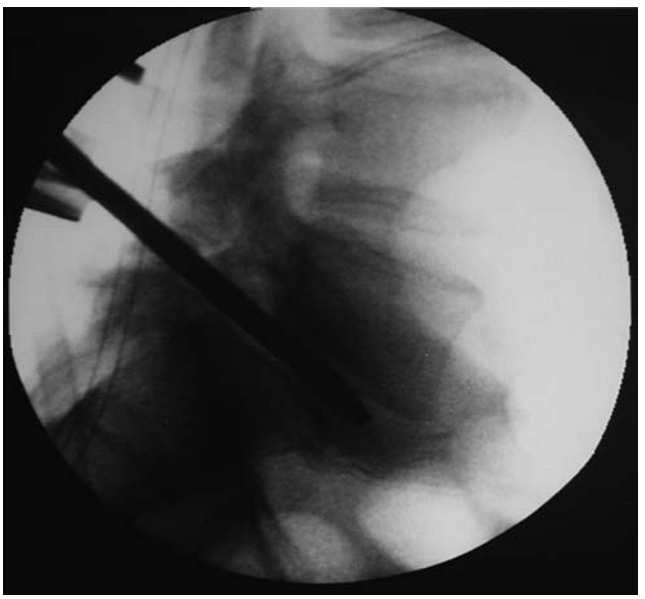

Fig. 15.5 Fluoroscopic image of interbody preparation

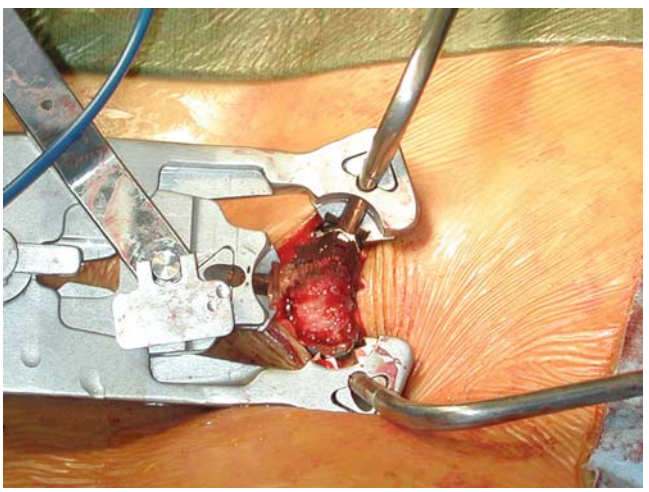

Fig. 15.4 Access driver secured (with attached lighting). (From Ozgur et al. [16]. Reprinted with kind permission of Springer Science+Business Media)

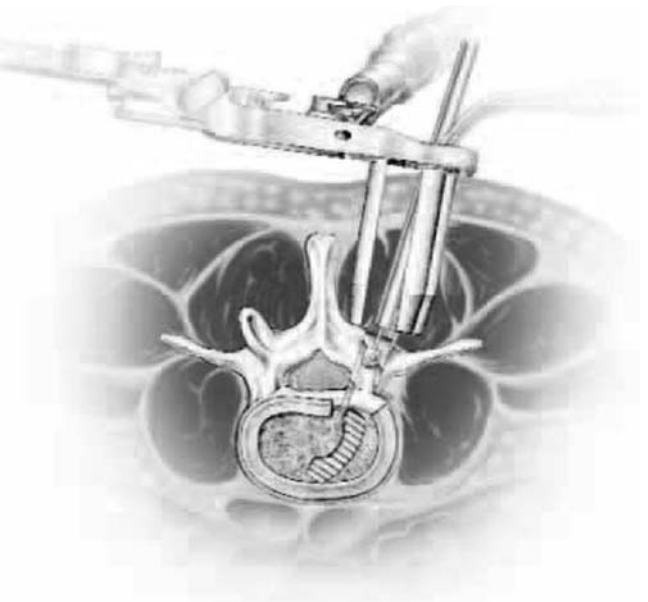

Fig. 15.6 Interbody graft placement. (From Ozgur et al. [16]. Reprinted with kind permission of Springer Science+Business Media and reproduced with permission of NuVasive, Inc.)

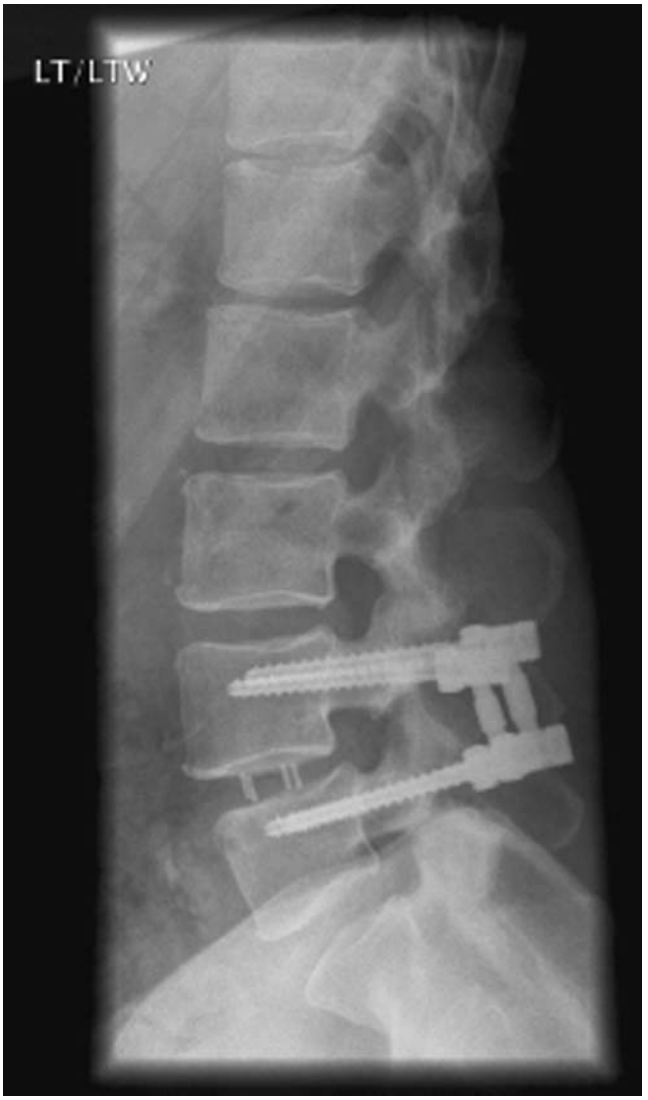

Fig. 15.7 Lateral fluoroscopic images demonstrating the TLIF and pedicle screws

nearly all our techniques could be safely performed simply with operative loupes.

Complications

Complications related to this exposure for the TLIF are rare. There are certainly risks inherent to performing laminectomies, foraminotomies, discectomies, and interbody fusions. However, the risks from performing this exposure are not much different than those from any other exposure. Classical bleeding and infection risks remain virtually the same. In fact, this minimally invasive exposure appears to have less morbidity involved, given the off-midline intramuscular approach rather than stripping off all the soft tissue during a typical open-midline approach. The inherent risks involve literally getting lost in the minimally invasive anatomy. Not knowing where one is anatomically can lead to trouble. Additionally, a minimally invasive exposure can make it more difficult to correct complications such as CSF leak and extensive bleeding. However, as with any new procedure, there are a learning curve as well as an education in morbidity avoidance. The key seems to be related to the initial retractor placement. If this is done well, then the operative corridor will be ideal and the rest of the case will usually go well. Therefore, providing extra time and attention in the beginning steps will prove to be a good investment.

Discussion

This minimally invasive system for implementing the TLIF is proving to be a good tool in a spine surgeon's armamentarium for the surgical correction of spinal disorders. It is a relatively straightforward system providing an excellent operative corridor for a variety of posterolateral spinal procedures, including laminectomy, hemilaminotomy/discectomy, foraminotomy, and TLIF. The most important considerations in this approach are whether or not the patient requires a direct decompression and has spinal instability.

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Lateral Approach for Anterior Lumbar Interbody Fusion (XLIF and DLIF)

16

Burak M. Ozgur and Lissa C. Baird

Introduction

Since 1991, when Obenchain described the first laparoscopic lumbar discectomy [1], the field of minimally invasive spine surgery has continued to evolve. Surgeon and patient alike have been attracted by the advantages of minimally invasive surgery, including less tissue trauma during the surgical approach, less postoperative pain, shorter hospital stays, and faster return to activities of daily living. These reported advantages led to the laparoscopic anterior lumbar approach and mini-open anterior lumbar interbody fusion (ALIF) becoming commonly performed procedures [2–7].

However, a greater acceptance of these minimally invasive procedures has been hampered by the known complications and challenges associated with endoscopic spine surgery. Reported problems include anesthetic complications [8], visceral damage [9], large vessel bleeding [10, 11], and sexual dysfunction [12, 13]. Surgeons attempting to use this surgical technique are challenged by the required technical skills, steep learning curve, and continued requirement for an access surgeon. This chapter describes a novel, minimally disruptive spine procedure called the Extreme Lateral Interbody Fusion (XLIF) (NuVasive, Inc., San Diego, CA) or the Direct Lateral Interbody Fusion (DLIF) (Medtronic, Memphis, TN).

This technique is novel in that it can be used to gain access to the lumbar spine via a lateral approach that passes through the retroperitoneal fat and psoas major muscle. Hence, the potential complications with an anterior transperitoneal approach to the lumbar spine can be avoided, major vessels are not encountered, an anterior access is not required, and the procedure can be done through a pair of 2-cm incisions. We describe the techniques of this approach to the lower lumbar spine.

Materials and Methods

Patient Selection and Surgical Indications

Patients who presented with axial low back pain without severe central canal stenosis were considered candidates for this surgery if they failed at least six months of conservative, traditional nonoperative management. Contraindications included significant central canal stenosis, significant rotatory scoliosis, and moderate to severe spondylolisthesis.

In some patients, functional anesthetic discography was used as a tool to assist in level selection. The group of patients is essentially the same as those with degenerative disc disease and considered candidates for fusion (ALIF) or more potentially lumbar disc arthroplasty. Figure 16.1 demonstrates images from a representative patient with degenerative disc disease at L2–L3.

Surgical Technique

Patient Preparation

With general endotracheal anesthesia achieved and intravenous lines started, the patient is placed in a true 90° right or left (depending on the patient's anatomy and its affect on potential surgical trajectory planning) lateral decubitus position, with the contralateral side elevated and taped in this position. A cross-table anterior-posterior (AP) image helps to confirm the true 90° position. The table and/or patient should be flexed in such a way as to

Burak M. Ozgur (✉)
Director of Minimally Invasive Spine Surgery, Assistant Professor of Neurosurgery, Department of Neurosurgery, Cedars-Sinai Medical Center, Los Angeles, CA 90048, USA
e-mail: bozgur@gmail.com

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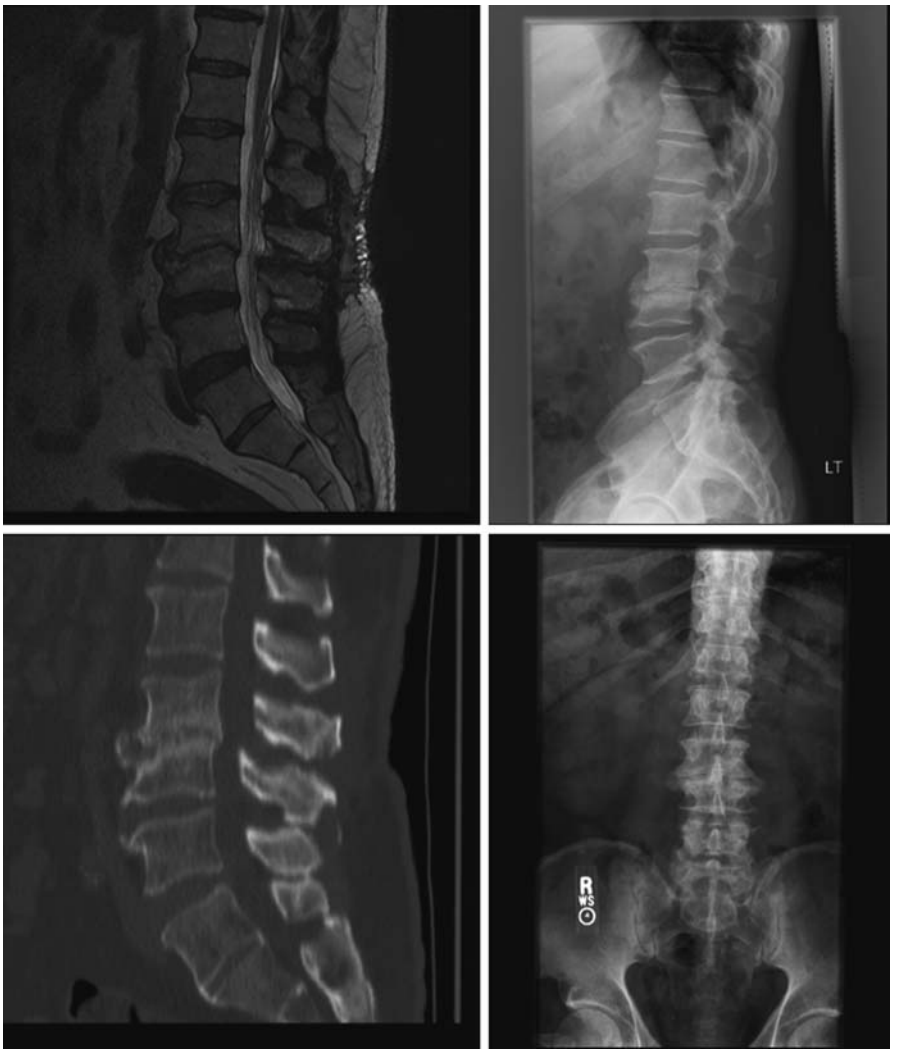

Fig. 16.1 Preoperative MRI, CT, and X-rays demonstrating L2-3 degenerative disc disease. (From Ozgur et al. [28]. Reprinted with permission from Elsevier)

increase the distance between the iliac crest and the rib cage, especially useful at upper lumbar levels and at L4–L5. After aseptic treatment of the skin, a radiopaque instrument or tool and lateral fluoroscopic image are used to identify the lumbar disc's mid-position (Fig. 16.2). A mark is made on the patient's lateral side, overlying the center of the affected disc space (Fig. 16.3). Through this mark, a small incision will be created for the insertion of atraumatic tissue dilators and an expandable retractor, which will be the working portal.

Retroperitoneal Access

A second mark is made posterior to this first mark at the lateral border of the paraspinal musculature. At this second mark, a longitudinal incision of about 2 cm is made to accommodate the surgeon's index finger, which is inserted anteriorly through the muscle layers [Fig. 16.4(a)] to identify the retroperitoneal space. Blunt dissection scissors are used to carefully spread the muscle fibers until the retroperitoneal space is reached. Care should be taken to avoid perforation of the peritoneum. After passing through the fascia and accessing the retroperitoneal space [Fig. 16.4(b)], the index finger is used to sweep the peritoneum anteriorly and then to palpate down to the psoas muscle. Once the psoas muscle has been identified, the index finger is swept up to the direct lateral target mark. An incision is made at this direct lateral location, and an initial dilator is introduced. The index finger, which is already in the retroperitoneal space, is used to escort the dilator safely from the direct lateral incision to the psoas muscle, protecting the intraabdominal contents [Fig. 16.4(c)]. The dilator is then placed over the surface of the psoas muscle, exactly over the disc space to be operated, as confirmed by AP and lateral fluoroscopy.

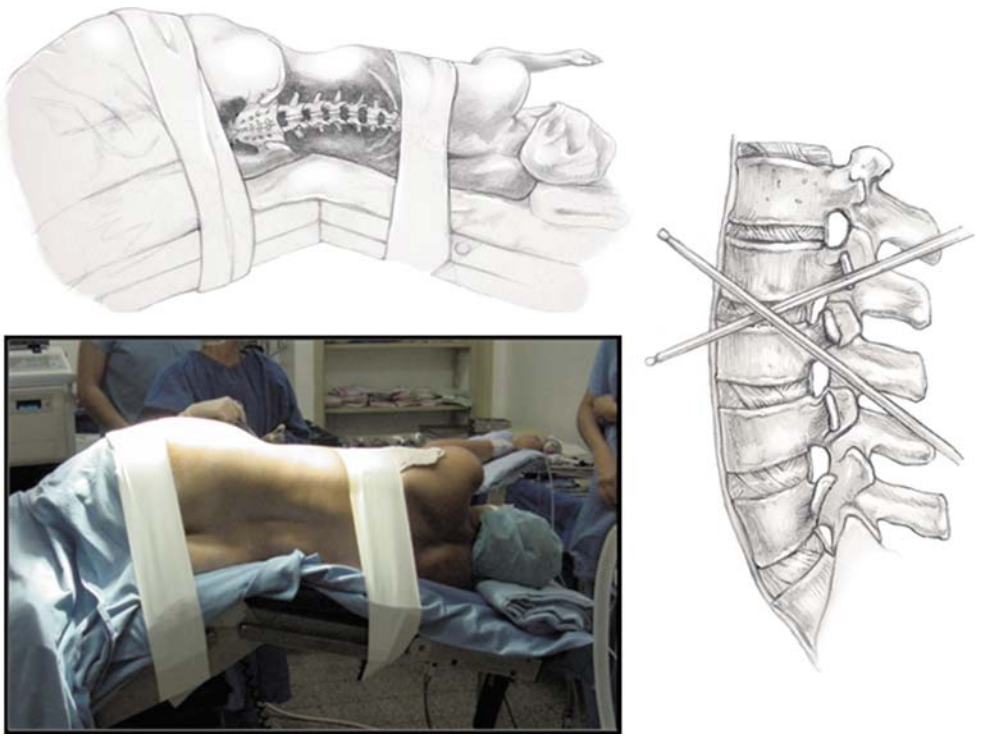

Fig. 16.2 Artistic renditions and actual OR picture demonstrating patient positioning and targeting

Fig. 16.3 Intraoperative photo demonstrating incision planning. (From Ozgur et al. [28]. Reprinted with permission from Elsevier)

Transpsoas Access

The fibers of the psoas muscle are then gently separated with the initial dilator using blunt dissection and the electromyographic (EMG) monitoring system to assess the close proximity of the lumbosacral plexus to the advancing dilator. Care should be taken to minimize trauma to the psoas muscle. The psoas should be parted between the middle and anterior thirds of the muscle, ensuring that the nerves of the lumbar plexus are located posteriorly and outside the operative corridor.

Additionally, direct lateral trajectory through the psoas ensures that the great vessels remain anterior to the operative corridor. The nerves are not visualized, and the size of the psoas muscle does not seem to be a factor in this technique. The dilators are insulated to minimize current shunting, while an isolated electrode at the distal tip acts as the stimulation source. In the posterior one third of the psoas muscle lie the descending nerves of the lumbar plexus [14–16]. The NeuroVision System by NuVasive assists with safe passage by these nerves or confirmation of their posterior location via evoked EMG monitoring. In Detection mode, the NeuroVision System will continuously search for the stimulus threshold that elicits an EMG response on the myotomes monitored and audibly and visually report the thresholds. As the dilator is advanced through the psoas muscle, the stimulus necessary to elicit an EMG response will vary with distance from the nerve; i.e., the closer the stimulus source is to the nerve, the less stimulus intensity will be required to elicit a response, and the lower the resulting threshold will be, providing an indication of the relative proximity of the dilator to the nerves [17, 18]. Experience has suggested that threshold values greater than 10 mA indicate a

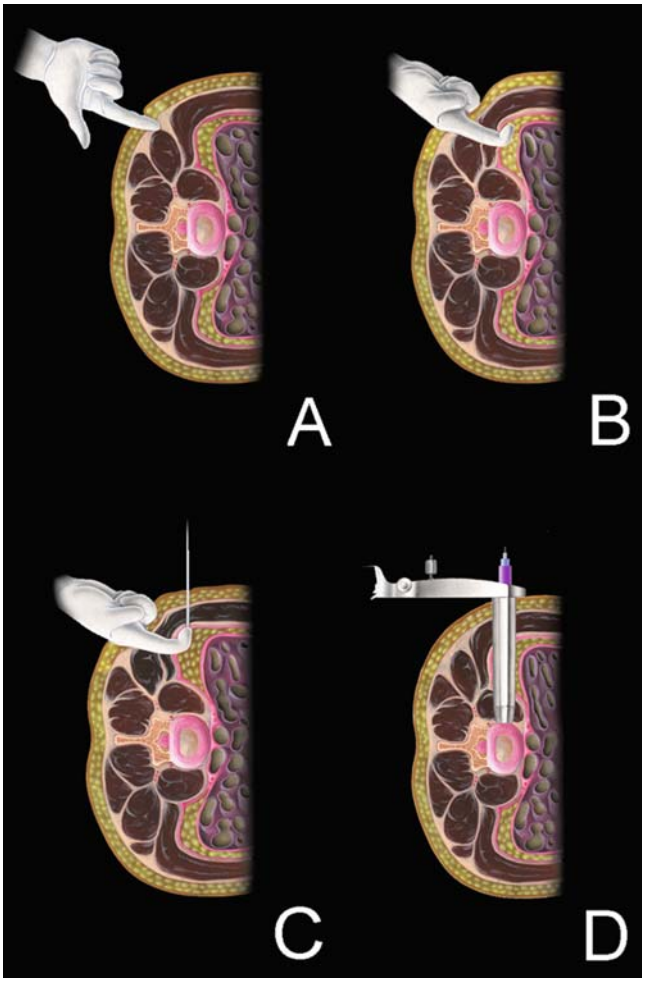

Fig. 16.4 Artistic demonstrations of finger dissection introducing and guiding down dilating tubes until retractor is docked through the lateral incision. (From Ozgur et al. [28]. Reprinted with permission from Elsevier)

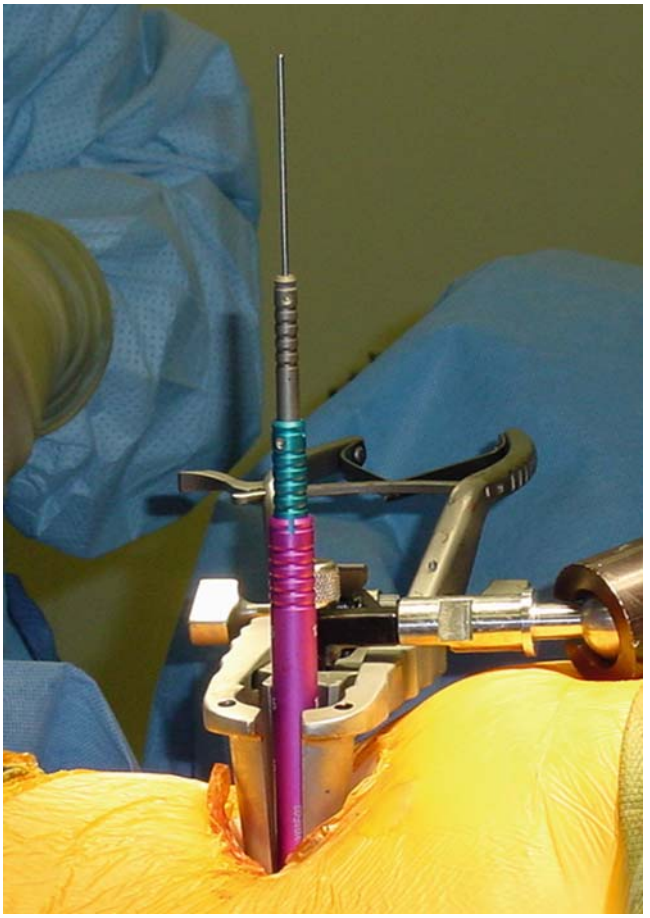

Fig. 16.5 Intraoperative photo demonstrating dilating tubes and retractor arm inserted. (From Ozgur et al. [28]. Reprinted with permission from Elsevier)

distance that allows for both continued nerve safety and ample working space.

Disc Exposure

The dissection continues, delicately spreading the mid-portion of the psoas muscle fibers laterally, while avoiding the lumbosacral plexus and genitofemoral nerve, until the surface of the disc has been reached [Fig. 16.4(d)]. The final position should be reconfirmed by fluoroscopy. Subsequent dilators are introduced, gradually spreading the psoas muscle until the retractor is inserted over the final dilator (Fig. 16.5). Cross-table AP fluoroscopy is used to confirm the position of the retractor blades on the lateral border of the spine. A rigid articulating arm is attached to both the retractor and the surgical table to provide hands-free retraction. The retractor blades are expanded in a cranio-caudal direction to the desired aperture by squeezing the retractor handles. An anterior-posterior exposure is achieved by turning the knobs on the sides of the retractor. Because the articulating arm is attached to the independent posterior blade, expansion by turning the knobs is preferentially anterior so as to minimize the blade pressure on the posterior portion of the psoas muscle and the nerves within it. The size of the exposure is customizable as needed and changeable intraoperatively.

A microscope or bifurcated light cable is used to provide direct light and visualization into the wound. The single end of the bifurcated cable should be passed off and attached to a xenon arthroscopy light source; the two remaining ends should be placed into the retractor blades and bent out of the way of the exposure. The operative corridor is thus established and should be thoroughly explored. Direct visualization and the stimulation-EMG testing of the operative field can verify safe passage into the interbody space. Bipolar electrocautery can be used to prepare the disc visualization.

Discectomy and Interbody Implant Placement

Under direct vision (Fig. 16.6), a thorough discectomy is performed using standard instruments such as an up-biting curette, pituitary rongeur, and various scrapers and broaches (Figs. 16.7 and 16.8). The anterior and posterior annulus is left intact, with the annulotomy window centered in the anterior half of the disc space and wide enough to accommodate a large implant. Disc removal and release of the contralateral annulus using a Cobb dissector provide the opportunity to place a long implant that will rest on both lateral margins of the epiphyseal ring, maximizing endplate support. Interbody distraction and implant placement in this anterior and bilateral epiphyseal position provide strong support for disc height restoration and sagittal and coronal plane imbalance correction. Typically, BMP and bone graft substances are inserted into the interbody space and interbody cage device.

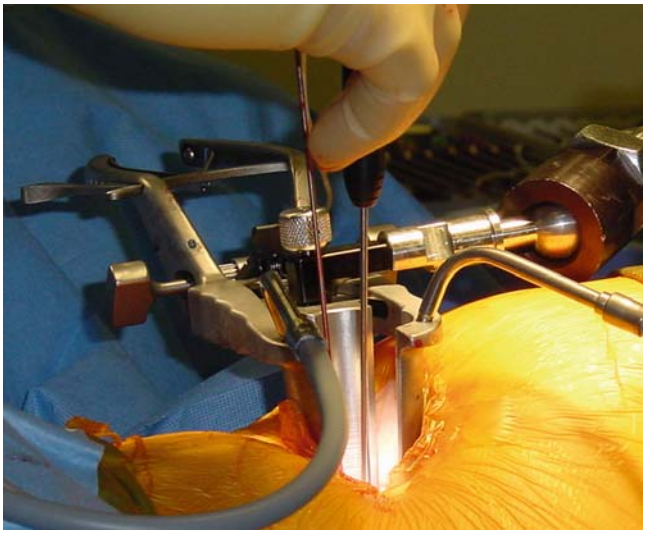

Fig. 16.7 Intraoperative photo taken while surgeon performing discectomy. (From Ozgur et al. [28]. Reprinted with permission from Elsevier)

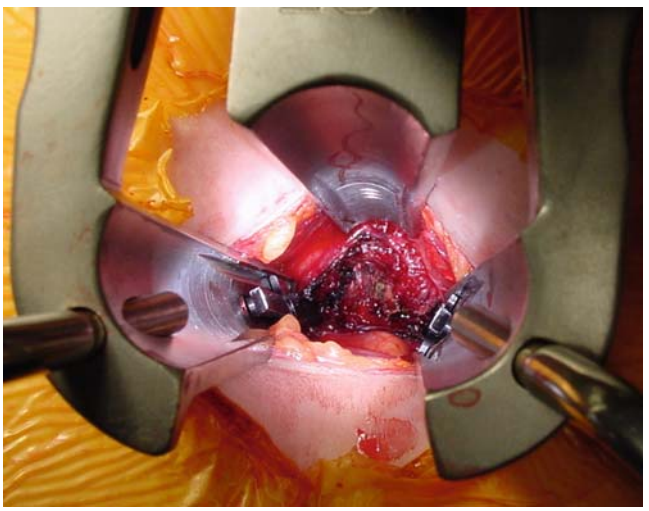

Fig. 16.6 Intraoperative photo taken looking down through retractor prior to discectomy. (From Ozgur et al. [28]. Reprinted with permission from Elsevier)

Closure

The exposure is copiously irrigated, and the retractor is removed slowly, so as to observe the psoas muscle rebounding and to confirm hemostasis. For both incision sites, the fascial layer is closed with 0-Vicryl and the subcutaneous layer is closed with 2.0-Vicryl sutures. A 4.0 monocryl is used for subcuticular closure followed by skin glue for the final layer of closure. No drains have thus far been required. Figure 1.7 demonstrates a well-healed

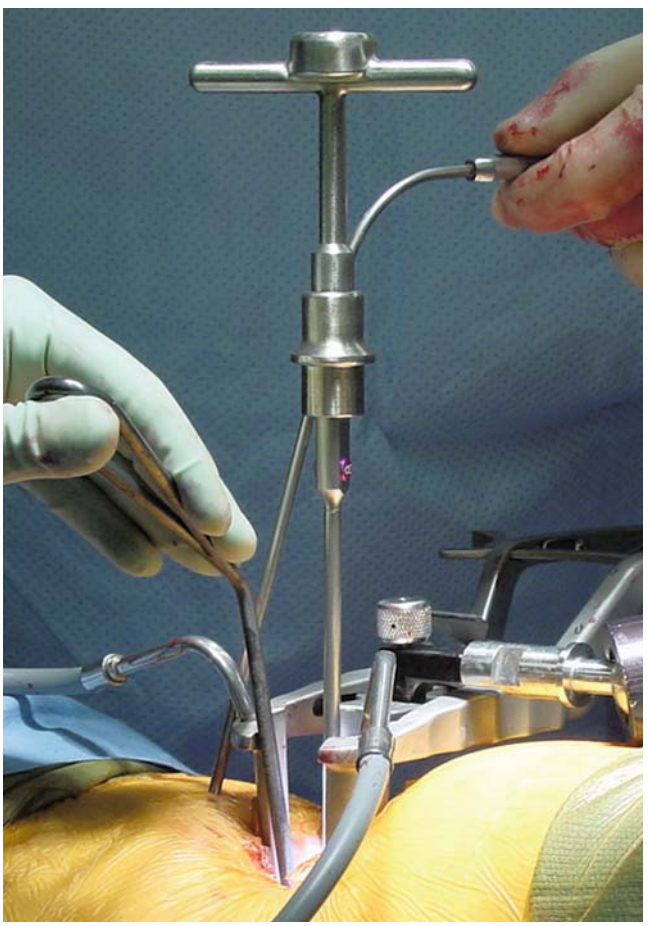

Fig. 16.8 Intraoperative photo taken with interbody cage placement. (From Ozgur et al. [28]. Reprinted with permission from Elsevier)

lateral surgical incision at about one month postoperation. The patient is then placed prone for the placement of percutaneous pedicle screws, or the screws and placed later at a second stage.

Results

During preoperative consultation, all patients were informed of all surgical options, including ALIF, posterior lumbar interbody fusion, transforaminal lumbar interbody fusion (TLIF), and XLIF/DLIF. A complete discussion and description of the XLIF/DLIF technique was described to all patients interested in the technique. An informed consent was attained for every patient.

The majority of XLIF or DLIF procedures were supplemented with percutaneous pedicle screw fixation (either immediate or staged), and all procedures concluded without complication. Figure 16.9 represents images from a patient having had an L3–L4 XLIF followed by percutaneous pedicle screw instrumentation. Nerve avoidance equipment alerted us to a nearby spinal nerve during the transpsoas approach in one patient, prompting redirection of the approach more anteriorly, away from the nerve, with no consequence. No postoperative intensive care unit stay or blood transfusions were required. The majority of patients needed only Vicodin or Percocet for analgesia and ambulated on postoperative day 1. Visual Analog Scale and Oswestry Disability Index were collected by our clinic nurse by means of a patient questionnaire that was filled out at every clinic visit. These follow-up results are forthcoming.

Discussion

New techniques and technologies continue to push the limits of minimally invasive spine surgery [19]. Laparoscopic ALIF has been reported to be a safe surgical technique [2] and is commonly performed [2–7]. The primary advantages over the open surgical approach are less tissue trauma, reduced postoperative pain, shorter hospital stays, and earlier return to work. Nonetheless, the advantages of laparoscopy over open techniques have recently been questioned [20].

Laparoscopic techniques are not without their complications. During the initial percutaneous approach, the bowel may be injured [9]. CO_2 insufflation may lead to physiological complications [8] such as low cardiac output, elevated mean arterial pressure, and elevated vascular and systemic resistance. Other reported complications have included injury to great vessels [10, 11], retrograde ejaculation [12, 13], and arterial thromboembolism [21]. Moreover, significant technical challenges limit the value of laparoscopic anterior approaches. Mastering the operative use of laparoscopic instruments is a significant challenge, especially if not routinely employed. Depth

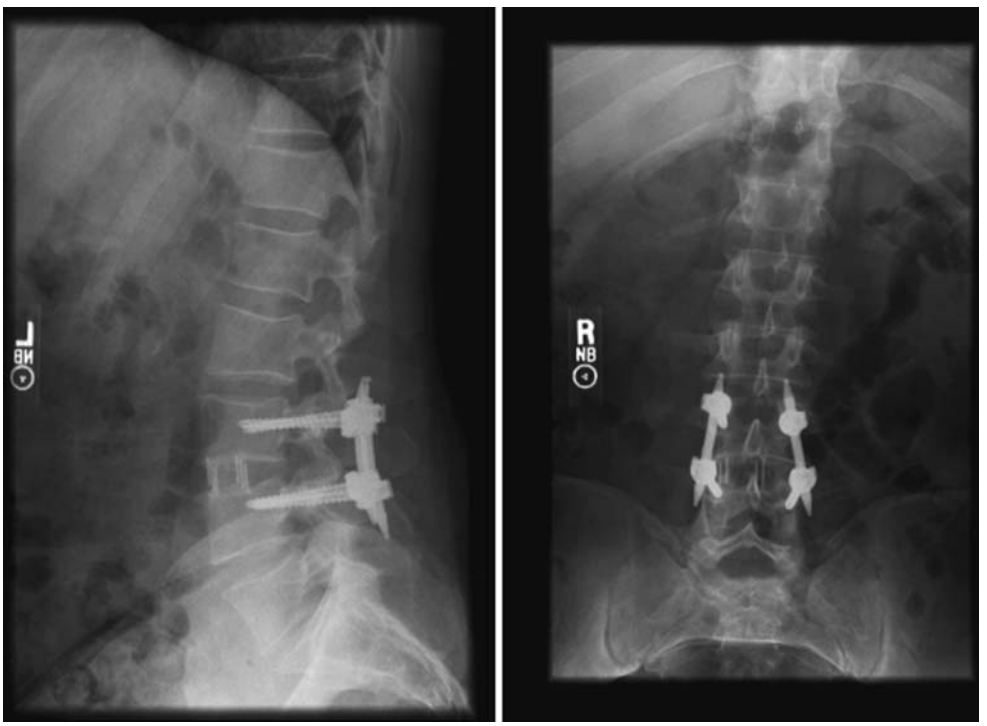

Fig. 16.9 Postoperative X-rays demonstrating an L3-4 interbody fusion and screw construct. (From Ozgur et al. [28]. Reprinted with permission from Elsevier)

perception is compromised with the use of two-dimensional video imaging. Access to the anterior lumbar spine at L4–L5 is particularly challenging with laparoscopy, given that it requires ligation of the iliolumbar vein and mobilization of the great vessels. Lastly, access to the anterior lumbar spine is still dependent on the general surgeon.

Reports have shown that the laparoscopic anterior lumbar approach offers no significant advantage over the mini-open approach [6, 22]. Recently, Kaiser et al. reported on 98 patients who underwent ALIF procedures, 47 via a laparoscopic approach and 51 via a mini-open technique [22]. A significantly longer preparation time was observed when using a laparoscopic approach versus a mini-open approach. The average procedural time for the laparoscopic approach was 185 minutes. Although some of our earlier cases took longer than this time, it is notable that there is a learning curve associated with using a new technique and trusting the nerve-monitoring equipment in avoiding nerve injury. Currently, we are averaging 45 minutes per XLIF level.

The XLIF technique is a modification of the retroperitoneal approach to the lumbar spine. The technique was first presented in 2001 by Pimenta, who has performed more than 100 lateral transpsoas surgeries since 1998 [23]. The equipment used in this procedure is uncomplicated, is conventional, and does not require additional capital expenditure. An operative microscope may be used but certainly is not required. In fact, thus far all of our cases have been performed simply using operative loupes. Furthermore, the attachable illumination provided by the MaXcess system enables unparalleled visibility without the discomfort of wearing a headlight.

When compared with anterior laparoscopic approaches to the lumbar spine, the lateral approach has several advantages. First, a general surgeon is not needed for access. A far-lateral approach eliminates the need to violate or retract the peritoneum, or to retract the great vessels. Second, compared with laparoscopic techniques, no steep learning curve exists for this minimally disruptive technique. All tissue dissection occurs under direct vision, without impairment of depth perception. Third, a far-lateral approach avoids many of the known complications of laparoscopic anterior approaches, such as damage to the great vessels during mobilization [10, 11] and retrograde ejaculation [12, 13] most likely from disturbance of the superior hypogastric nerve plexus. Fourth, the most significant advantage we report between the laparoscopic ALIF and the XLIF/DLIF is in operative time. When compared with a mini-open laparotomy, a laparoscopic ALIF has been noted to have a longer operative time [24].

Limitations do exist with this far-lateral approach. First, the inferior edge of the 12th rib and the superior edge of the iliac crest potentially limit the classic exposure sites to L1–L2, L2– L3, L3–L4, and L4–L5 (however, we have been able to perform this procedure all the way up to T10-11 in adult degenerative scoliosis by inserting the retractor in between the ribs). Also, dissecting the psoas major, though technically straightforward, must be done carefully so as not to injure the nerves of the lumbar plexus or cause significant trauma to the psoas major. Prior reports of lateral retroperitoneal approaches included mobilization of the psoas muscle from the lumbar spine, but a high incidence of transient numbness along the genitofemoral nerve has been reported after retraction of the psoas muscle [25, 26]. Because the XLIF/DLIF approach requires far less retraction, dilation, and dissection of the psoas muscle, transient sensory deficits along the anterolateral thigh and iliopsoas weakness may still occur, but to a far less symptomatic degree and shorter duration if at all. Use of the EMG monitoring system is critical to the safe passage by the nerves within the psoas muscle itself. As with most minimally disruptive spinal techniques, intraoperative fluoroscopy use is critical. The actual timing of the fluoroscopy use is important; however, it is significantly affected by the experience of the technician as well as that of the surgeon. We found that our fluoroscopy time was decreased; however, quantitative analysis has not been performed thus far. We hope that we can provide this information in future follow-up studies.

The surgical results of this procedure have shown that it is a safe and reproducible technique. It has demonstrated the benefits of a minimally invasive procedure, with quick recovery and improvements in pain and function scales. It has also demonstrated that the underlying objectives of surgery need not be compromised for the sake of less morbidity. Disc heights were restored and stability maintained by preserving ligamentous structures and inserting a large interbody implant. This can indirectly improve the foraminal volume and result in a reduction of radiculopathy. Sagittal balance was maintained or improved by placing the implant in an anterior position. Coronal imbalances were corrected by ensuring full bilateral endplate coverage by the implant. Longer follow-up patients in this study have shown solid fusion progression, apparently uncompromised by the technique.

Conclusion

Given the known complications and challenges of endoscopic spine surgery, the lateral ALIF may be a valuable alternative to laparoscopic anterior approaches for an

interbody spine fusion. Subsequent articles shall report our longer-term follow-up data and efficacy. As comfort with this technique expands, so too do the indications for it. It has more recently also been used to treat low-grade spondylolisthesis and adult degenerative lumbar scoliosis with great success [27]. Longer follow-up is certainly required, but early results are encouraging. Time and increased numbers will also help us in determining the fusion rates for future studies. Furthermore, we are in the process of trying to come up with a control group as well as a more traditional surgical group for comparison.

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Anterior Lumbar Interbody Fusion (ALIF) 17

Henry E. Aryan, Sigurd H. Berven, and Christopher P. Ames

Introduction

Anterior lumbar interbody fusion (ALIF) is a method of achieving intersegmental arthrodesis that is indicated for the treatment of symptomatic degenerative disease [1, 2]. While ALIF has use for indications involving multiple levels and complex combinations of anterior and posterior instrumentation, fusions for degenerative and deformity cases, spondylolisthesis [3, 4], and failed posterior surgery with pseudoarthroses, a common indication remains the treatment of symptomatic degenerative disc disease. The symptomatic degenerative disc often presents with aching low back pain that radiates into the buttocks and sacroiliac areas. It is often associated with activity. Radiographic evaluation can often be characterized by a loss of intervertebral height, endplate changes, and facet arthrosis. Magnetic resonance imaging (MRI) can often be characterized with decreased signal on T2-weighted images, indicative of dehydration. On MRI there is frequently evidence of high-intensity signal that may represent annular tearing, and edema in the adjacent vertebral bodies around the endplates [5–7]. The use of discography to determine appropriate surgical levels remains somewhat controversial, as it has not proven to be a strongly reliable indicator of good outcomes [8].

ALIF procedures have been historically divided into three main types: open, mini-open, and laparoscopic. There is little clear evidence that shows a specific generic advantage of one approach over the others. Each individual case may have specific features that provide for better application of one approach over the others. However, the surgeon's comfort and preference for one approach are often the best discriminator to help determine which operative approach is best suited for each particular case. Consideration should be given to age, bone quality, comorbidities, and previous surgeries or infection, as each of these may increase the risk of intraoperative complications or the failure of interbody fusion devices. Postoperative complications of thrombolic and thromboembolic disease are more likely in older patients and those with stiffer vessels that required more vigorous retraction intraoperatively [9].

Contraindications are relative and should be considered case by case. The use of standalone cages may yield less satisfactory results and result in significant subsidence when used alone in osteopenic bone or when the endplates are otherwise incompetent. The use of metal, foreign-body implants in cases of active infection should be avoided whenever possible [9]. Complete debridement of infected tissue and reconstruction with a metal cage are possible, but definitive implantation should be postponed until the infection has been completely treated when possible. Previous infection, radiation therapy, vascular surgery, or anterior spinal surgery may create significant adhesions of the great vessels and may make surgical dissection very difficult, greatly increasing the risk of intraoperative vascular injury and complications.

Common complications of surgery may include failure of fusion, neural injuries, vascular injuries, and damage to the abdominal wall or paralysis of the rectus abdominus [10]. Many of these common complications are a result of difficulty with exposure and visualization. The poor placement of cage or allograft fusion devices can result in nonunion or fusion in a suboptimal position. The ability to prepare the disc space and endplates can be compromised by poor visualization and result in suboptimal grafting or device positioning. Damage to the presacral neural plexus can result in retrograde ejaculation and sympathetic dysfunction [10, 11]. The plexus can be injured during dissection in the periosteal plane anterior to the lumbosacral junction. This again can be the result of poor visualization while dissecting and is theoretically more common during

H.E. Aryan (✉)
Department of Neurological Surgery, University of California-San Francisco, San Francisco, CA 94143; Sierra Pacific Orthopaedic & Spine Center, Fresno, CA 93720, USA
e-mail: draryan@draryan.com

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laparoscopic surgeries than with open or mini-open techniques. The iliolumbar vein is commonly ligated during the surgical approach, most commonly at the L4–L5 level. If the vein is not ligated, excessive retraction on the left common iliac and poor visualization of the surgical field can result [9, 12]. It may also predispose the vascular tree to direct injury and to thromboembolic complications, including pulmonary embolus and infection [10]. The most common vascular injuries are tears of the left common iliac vein, which can usually be repaired directly with a small monofilament suture [12]. More complex tears may require a vascular surgeon's assistance. Other complications can include ileus and bowel injury [11]. Preoperative evaluation of the vascular anatomy and correlation with operative levels by computed tomography have been shown to be quite reliable and might be useful in planning the operative approach and assessing the spine surgeon's desire to have a vascular surgeon participate in the exposure [13].

An examination of outcomes is a good opportunity to compare the mini-open and open techniques. Provided that adequate visualization can be achieved intraoperatively with both the open and mini-open approaches, there appears to be no significant advantage to utilizing the more extensive open surgical approach with regard to preventing complications or achieving satisfactory long-term outcomes. There is some suggestion that the mini-open extraperitoneal approach may yield some advantages in terms of less blood loss and decreased operative times [14]. By comparing the incidence of common intraoperative and postoperative complications and outcomes, it is easy to understand why there is no clear advantage to the laparoscopic surgical technique for anterior lumber interbody fusion, and there is theoretically a higher incidence of intraoperative complications [15–18]. The exposure is often potentially less adequate and may also lead to suboptimal surgical outcomes [19]. For this reason, many surgeons are choosing mini-open techniques in order to improve the efficiency and visualization they have during surgery while maintaining similar short- and long-term outcomes [20].

Technique

Preoperative Planning

A thorough preoperative plan is critical. Prior to the performance of any anterior spinal surgery, the following steps are recommended:

- Perform a thorough review of preoperative patient X-rays to identify any possible contraindications to ALIF or arthroplasty and to gain a preoperative estimate of the implant's size and angle. A preoperative evaluation of the patient's history, symptoms, and radiological studies needs to verify that the suspect lumbar disc is the significant pain generator. Often, discograms or diagnostic blocks are necessary to verify the site(s) of pain generation.
- Coordinate with a vascular or general surgeon trained as a spinal access surgeon if necessary (Fig. 17.1).
- Place the patient on a radiolucent operating table that will allow for C-arm movement. Intraoperative adjustability of lordosis using a hinged table or inflatable pillow is often useful during implant placement.

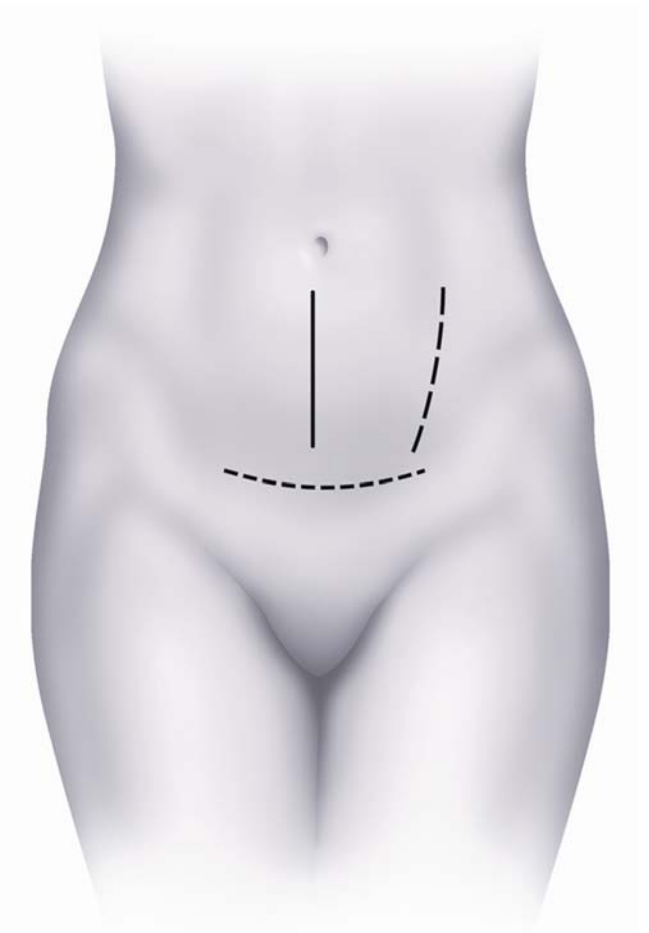

Fig. 17.1 Incision sites for anterior lumbar exposure. (From Aryan et al. [21]. Reprinted with permission from Elsevier)

Patient Positioning

- Place the patient in a supine position on a folding table or over an inflatable pillow (Fig. 17.2).
- Align the break in the table or the inflatable pillow directly under the affected disc.
- The disc space can now be opened by breaking the table (or inflating the pillow) to extend/increase

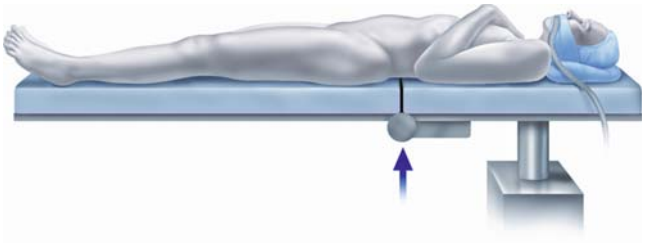

Fig. 17.2 Patient positioned on operating room table. Note that the break of bead is at the lumbar area. (From Aryan et al. [21]. Reprinted with permission from Elsevier)

lordosis of the spine or closed by flattening the table (or deflating the pillow) to flex/decrease lordosis of the spine.

- Position the patient's upper limbs so that there is space for circumferential C-arm movement over and around the operative level.

Surgical Approach

- Make a left paramedian skin incision (Figs. 17.1 and 17.3).
- Retract the underlying subcutaneous tissue until the fascia is exposed. Divide longitudinally with dissecting scissors.

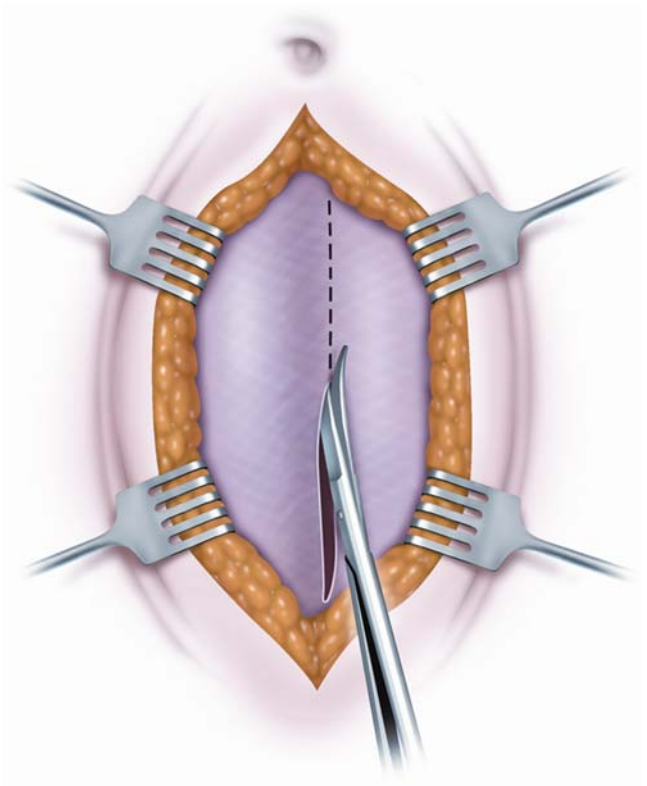

Fig. 17.3 Incision of rectus fascia. (From Aryan et al. [21]. Reprinted with permission from Elsevier)

- Retract the left rectus muscle to the left with fingers or blunt retractors (Fig. 17.4).
- Raise the underlying fascia. Divide longitudinally with dissection scissors or blunt dissection (Fig. 17.5).
- Identify the psoas, iliac artery, and iliac vein (Fig. 17.6).

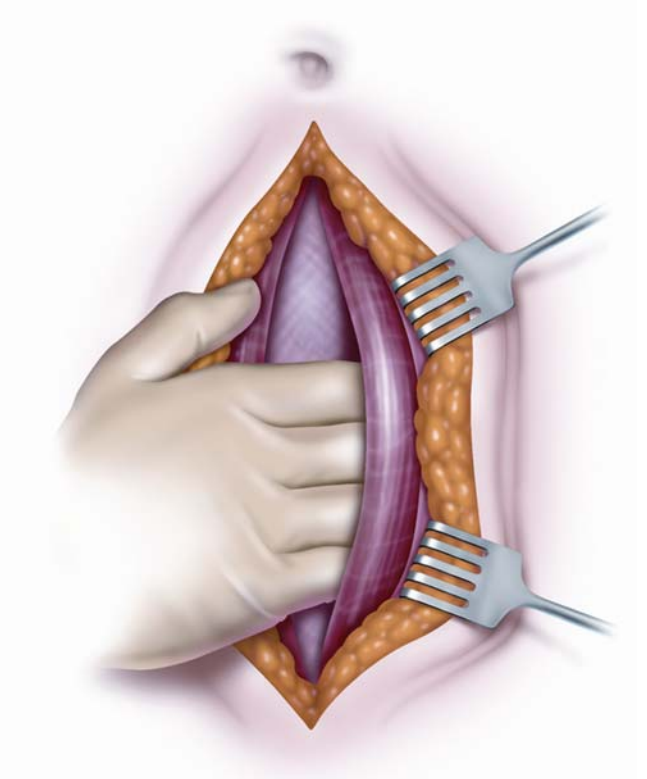

Fig. 17.4 Blunt dissection behind rectus abdominus muscle. (From Aryan et al. [21]. Reprinted with permission from Elsevier)

Approach of L5-S1

- Expose the L5-S1 intervertebral disc and ligate the median sacral vessels (Fig. 17.7).
- The further dissection of the tissue anterior to the intervertebral disc is mainly by blunt dissection. Careful attention to dissection and avoidance of electrocautery are advised. This dissection is carried first to the left and then to the right to achieve the maximum possible lateral exposure of the disc.
- Extreme care should be taken to protect the left and right common iliac vessels.
- Bluntly mobilize the left common iliac vein and artery with small swabs and then the right common iliac artery together with the right common iliac vein that lies posterior.
- All of these vessels are retracted laterally and occasionally slightly superiorly (Fig. 17.7).

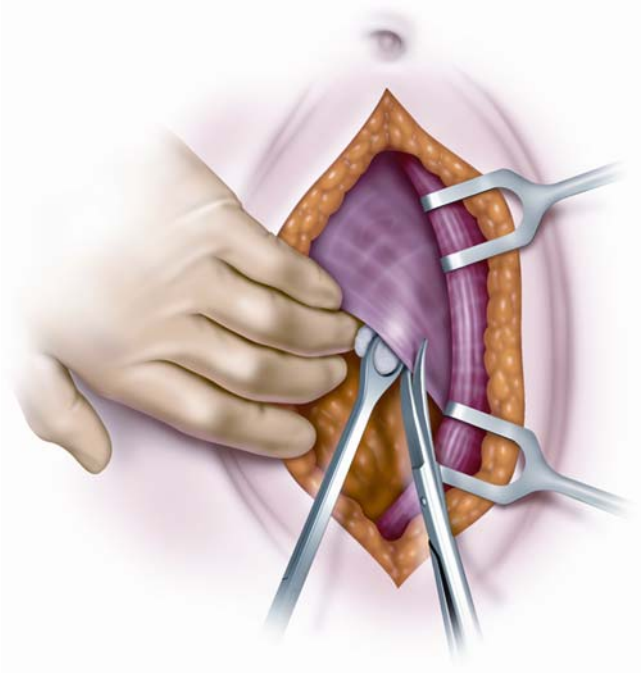

Fig. 17.5 Incision of oblique abdominal musculature. (From Aryan et al. [21]. Reprinted with permission from Elsevier)

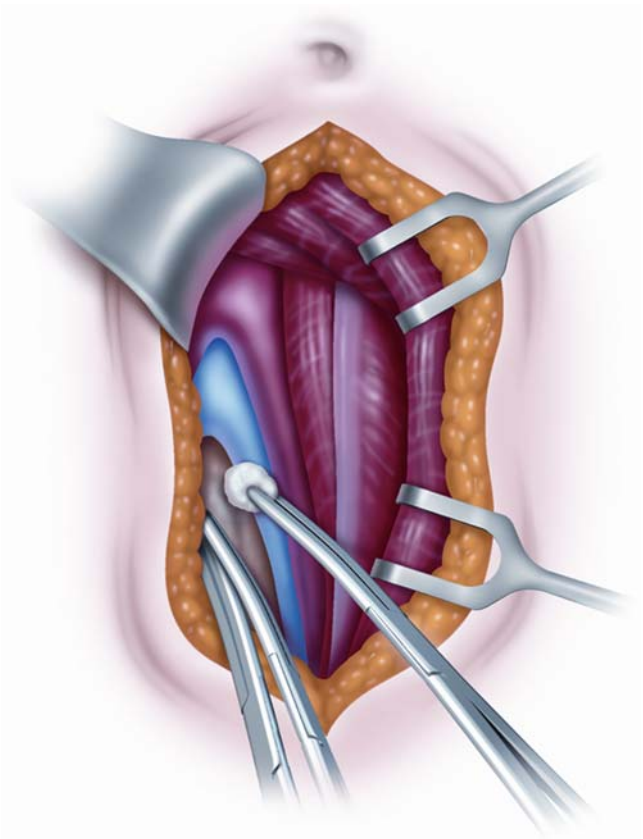

Fig. 17.6 Blunt dissection into retroperitoneal space. (From Aryan et al. [21]. Reprinted with permission from Elsevier)

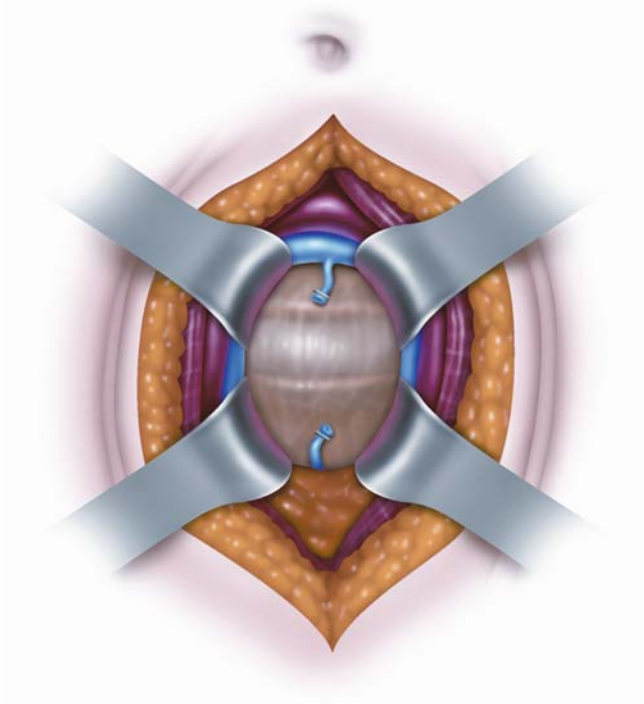

Fig. 17.7 Anterior lumbar exposure of disc space. (From Aryan et al. [21]. Reprinted with permission from Elsevier)

- Carefully impact four retractor pins into the adjacent vertebral bodies, or use an appropriate external soft tissue retractor system (Figs. 17.8 and 17.9).

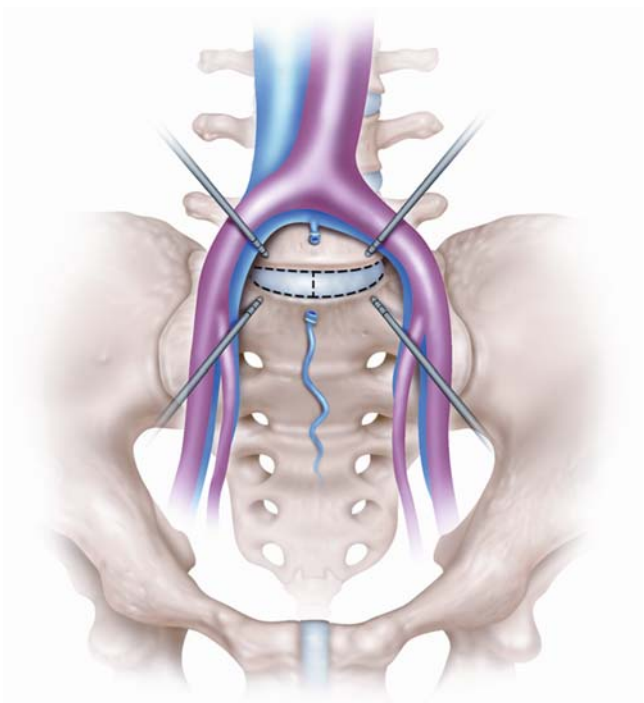

Fig. 17.8 Location of iliac vessels as it pertains to L5–S1 disc space. (From Aryan et al. [21]. Reprinted with permission from Elsevier)

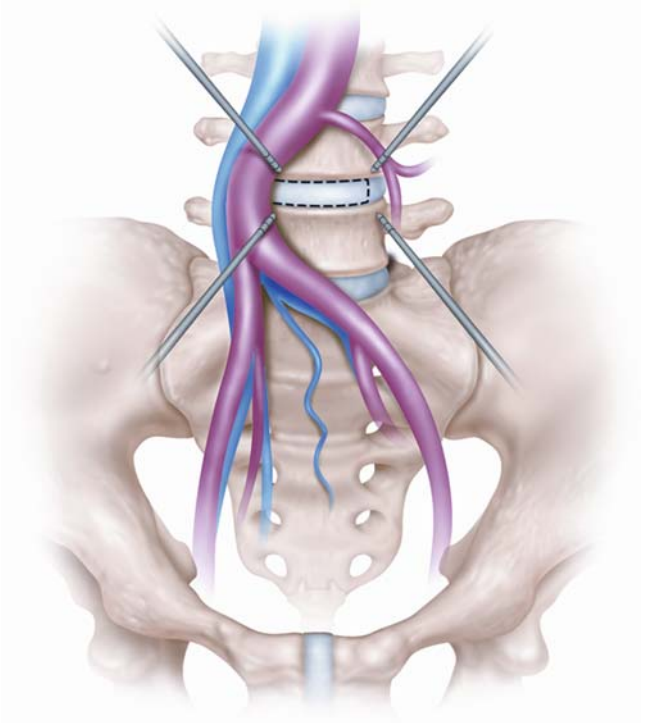

Fig. 17.9 Location of iliac vessels as it pertains to L4–L5 disc space. (From Aryan et al. [21]. Reprinted with permission from Elsevier)

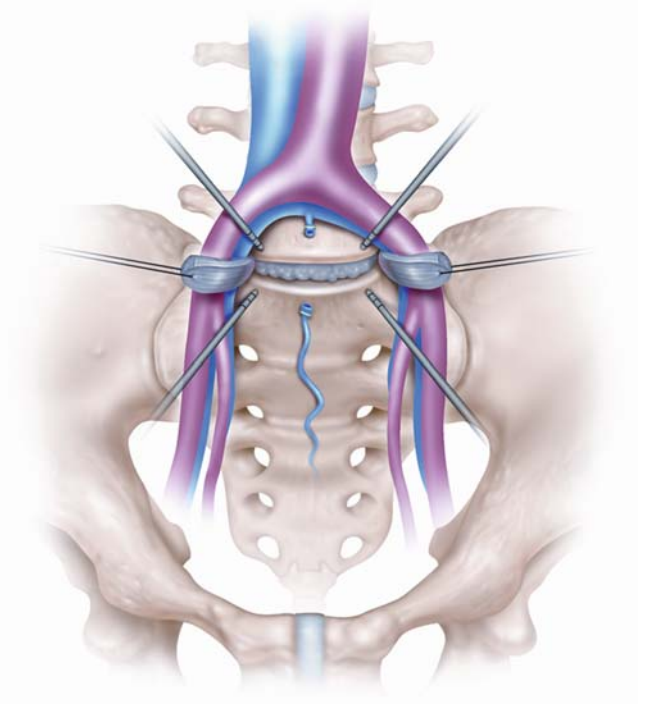

Fig. 17.10 Further lateral retraction with handheld retractors, which is usually required for arthroplasty. (From Aryan et al. [21]. Reprinted with permission from Elsevier)

- Verify the vertebral level by lateral fluoroscopy.
- Utilize a midline incision to open the anterior annulus. The flaps may be used to protect eccentric vessels.
- Mobilize the iliac vein, iliac artery, vena, cava and aorta to the right. Carefully impact four retractor pins into the adjacent vertebral bodies, or use an appropriate external soft tissue retractor system (Fig. 17.10).
- Verify the vertebral level by lateral fluoroscopy.
- Utilize a leftward incision to open the anterior annulus. The flap may be used to protect eccentric vessels.
- If desired, hold the annulus fibrosus in position with a suture and mosquito clamp.

Complete Discectomy

Performing a complete discectomy is critical for proper ALIF or artificial disc implantation. Complete discectomy, including the removal of the posterior lateral recesses of the disc, facilitates the following:

- Parallel distraction, which allows for the restoration of intervertebral height and sufficient opening of the neuroforamen
- Parallel alignment of the inner surfaces of the endplates, which provides uniform loading of implants
- Sufficient space for the largest-possible size implant.

Discectomy Technique

- Perform the initial central discectomy using rongeurs, curettes, and/or the disc elevator (Fig. 17.11).
- Care must be taken not to damage the bony endplate.
- Apply controlled distraction using the spreading and insertion forceps to visualize and remove the remaining disc tissue, leaving only the lateral annulus.
- It is imperative to remove the posterior lateral recesses of the disc and to release the posterior annulus when performing an arthroplasty.

Endplate Preparation

- Remove the cartilaginous endplate with the curettes, utilizing a side-to-side motion.
- Care must be taken not to damage the bony endplate.
- When necessary, carefully shape curved vertebral surfaces by removing dorsal and ventral osteophytes, utilizing the curettes and rongeurs or other appropriate instruments to ensure optimal placement of intervertebral graft or artificial disc prosthesis.
- Preservation of the integrity of the cortical endplate of the vertebral body is imperative because the

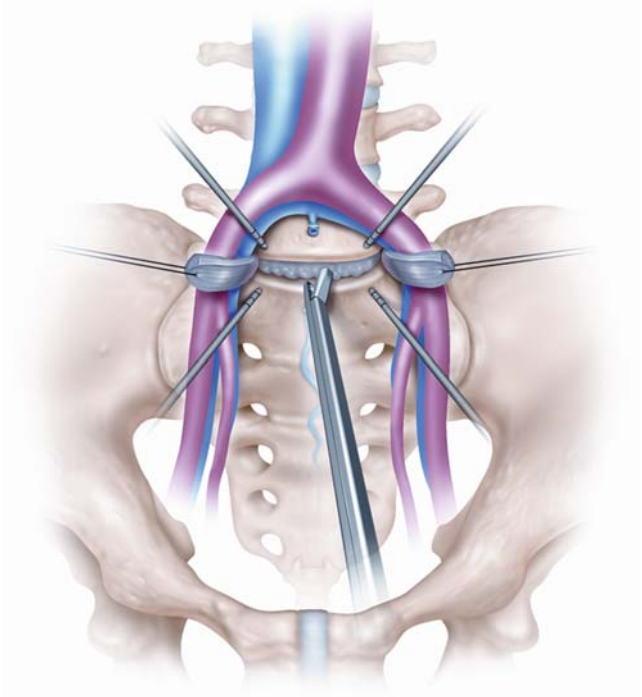

Fig. 17.11 Discectomy at the L5–S1 level. (From Aryan et al. [21]. Reprinted with permission from Elsevier)

preserved endplate provides a firm base for mechanical stability and reduces the potential for subsidence.

Fluoroscopy

Achieving a good AP film to define the midline of the vertebral body is critical to proper placement of intervertebral graft or artificial disc prosthesis. Positioning the fluoroscopic X-ray machine at the correct angle and position to get a good AP film can be challenging but is worth the effort in time and patient outcome. Positioning fluoroscopy so that the pedicles are of equal size and magnification as well as equidistant from the spinous process is a good tip to aid in the placement of grafts or prostheses.

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Percutaneous Pedicle Screw Placement for Spinal Instrumentation

18

Hormoz Sheikh, Ramiro A. Perez de la Torre, Oksana Didyuk, Vickram Tejwani, and Mick J. Perez-Cruet

Introduction

Spinal instrumentation has a long history, beginning with Hibbs [1] in 1911, who performed a posterior spine fusion for deformity. However, it wasn't until 1962 [2], when Harrington began using distraction rods, that internal spinal instrumentation gained more widespread use. Luque further refined this technique by introducing segmental instrumentation in 1982. The modern era of lumbosacral spinal fixation was ushered in by the work of Roy-Camille et al. [3] with the use of universal instrumentation based on pedicle screw implants.

A number of studies have shown the benefits of maintaining the posterior supporting anatomical architecture of the spine (i.e., muscles and ligaments) when performing spine surgery [4–12]. Traditional approaches used for posterior spinal instrumentation involve detaching the muscular and ligamentous structures from the spine to allow for visualization and palpation of the bony anatomy when placing pedicle screw instrumentation. This process causes significant harm to the muscles and ligaments, which can result in muscle atrophy and reduced function. Numerous studies have shown the detrimental effects during the retraction of the multifidus and erector spinae muscles while performing spine surgery [13]. Additionally, revascularization, denervation, and injury to the adjacent facet joint during traditional open procedures have been shown to result in transitional syndrome, leading to canal stenosis [14]. As a result of transitional syndrome, patients frequently undergo additional surgery with the need for decompression and extension of the fusion and instrumentation to adjacent levels. The cascade of events can then recur on adjacent levels, requiring additional surgery. Our theory is that by disconnecting the supporting musculature and ligaments of the spine from the bone architecture, a relative instability is created between the fused instrumented segments and the noninstrumented segment. In doing so, the body reacts by "laying down" tissue (i.e., the facets and ligaments hypertrophy) at the transitional zone to reduce the relative instability or nonphysiological motion. Significant hypertrophy of the facets and ligaments contributes to the transitional syndrome, which leads to canal and foraminal compromise and stenosis. Maintaining the posterior muscular and ligamentous anatomy reduces or eliminates this iatrogenic adjacent-level instability. In the senior author's series of minimally invasive spinal fusion patients, transitional syndrome rarely develops. Ultimately, this leads to better spine health, improved outcomes, and fewer reoperative procedures.

In an attempt to prevent the cascade of events leading to "failed back syndrome" as well as to maintain the natural integrity of the spinous structures, minimally invasive spinal instrumentation techniques have been developed [15]. These techniques employ the use of fluoroscopic or image guidance navigation to facilitate pedicle screw instrumentation without the need to disrupt the midline structures of the spine. The benefits are numerous, including smaller incisions, maintenance of muscular and ligamentous attachments to the spine, no need to expose the spine, minimal blood loss, and safe and accurate pedicle screw application. Increasingly, studies have shown the clinical benefits of these procedures when treating patients suffering from chronic debilitating back and/or leg pain due to degenerative disc disease and spondylolisthesis, with or without spinal stenosis [6, 7, 12, 16].

This chapter describes two different techniques that have been used safely and effectively for accurate percutaneous pedicle screw placement for spinal instrumentation. The advantage of these techniques is that they do not require open exposure of the bony landmarks for screw placement, which can result in significant paraspinal muscle injury and postoperative discomfort. Instead, pedicle

H. Sheikh (✉)
Department of Neurosurgery, Providence Medical Center, Michigan Head and Spine Institute, Southfield, MI 48075, USA

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screws are placed under fluoroscopic guidance. The instruments and equipment requirements for accurate percutaneous pedicle screw placement are shown in Table 18.1; many of these are available in the standard OR setting.

Table 18.1 Instruments and equipment requirements for accurate percutaneous pedicle screw placement

1. Fluoroscopic unit
2. Lead drape including thyroid shield for surgeon and operative personnel
3. Radiolucent table and frame that permits adequate anteroposterior (AP) and lateral fluoroscopic visualization of the spine
4. Cannulated instruments for pedicle screw placement
5. K-wire and K-wire driver
6. Jamshidi needle or P-C Pedicle Access Device (Abbott Spine, Austin, TX)

The patient is positioned prone on a radiolucent frame, or a Jackson table is used. We found that the Jackson table, with its relatively open area below the table platform, is ideal, particularly when targeting the S1 pedicle, since the framework of the C-arm may require it to be positioned at a significant coronal angle with respect to the table; tables with a central platform inhibit this C-arm position. The C-arm is sterile-draped to provide AP and lateral images without contaminating the field when repositioning the fluoroscopic unit from an AP view to a lateral view. After the necessary bone graft material is placed, the fluoroscopic unit is brought into the surgical field to view an AP image of the spine. The first step in accurately cannulating the pedicle is to position the C-arm so as to look down the pedicle. This is performed in the AP fluoroscopic view by placing the targeted vertebrae in the center of the fluoroscopic image seen on the monitor to prevent parallax distortion. The junction of the lateral facet and transverse process is targeted [Figs. 18.1(a), (b)], and then a lateral fluoroscopic view determines the depths of the tip of the Jamshidi needle [Fig. 18.1(d)]. The skin can be marked using a radiopaque instrument to determine the entrance incision on the skin prior to targeting the pedicle.

The C-arm in the AP view is positioned on the coronal plane to look straight down the targeted pedicle. This is achieved by making sure that the endplate of the targeted vertebral body is viewed as one line (i.e., the vertebral body is not tilted in the AP view of the coronal plane) and that the spinous processes are positioned in the midline [Fig. 18.1(b)]. For heavy-set individuals, manipulation of the contrast mode or collimation of the fluoroscopic unit may be required to adequately visualize these landmarks. Once adequately positioned, the two pedicles on the vertebral body should be clearly visualized; especially important is viewing the medial border of the pedicle since violating this border by either a K-wire or targeting needle can result in neural element injury. Viewing the pedicles on adjacent vertebral bodies above or below the targeted level can help to define the anatomy of the targeted pedicle. This is particularly true when targeting the sacrum (S1), where the pedicle can be hard to visualize due to the relative absence of the rostral or superior and lateral borders of the pedicle.

Pedicle Access Using a Lateral-to-Medial Trajectory

A Jamshidi needle is used to dock on the junction between the facet complex and transverse process [Figs. 18.1(a), 18.1(b)]. The Jamshidi needle is then advanced through the pedicle, making sure not to cross the medial border of the pedicle until the junction between the pedicle base and vertebral body has been reached [Figs. 18.1(c), 18.1(d)]. The procedure is performed by fluoroscopic visualization in the AP and lateral planes as the Jamshidi needle is advanced through the pedicle with gentle tapping using a mallet; a similar technique is used when performing vertebroplasty or kyphoplasty. Once the junction between the base of the pedicle wall and the vertebral body has been reached, the Jamshidi needle can be directed in a more medial fashion. The Jamshidi needle is typically passed to one quarter or one half the depth of the vertebral body and then a K-wire passed down the Jamshidi needle [Figs. 18.1(d), 18.1(e)]. The K-wire is then passed a little farther to seat it into bone, and the Jamshidi needle is then carefully removed. An assistant holds the K-wire with a Kocher clamp to assure that it is not pulled out of the vertebral body while removing the Jamshidi needle. At this step, easy dislodgement of the K-wire can occur; therefore, a slow upward twisting of the Jamshidi needle is needed. A series of cannulated muscle dilators is then passed over the K-wire to prevent the soft tissue from going into the threads of the tap and pedicle screw as they are passed down the K-wire. While passing cannulated instruments over the K-wire, an assistant should hold the K-wire with a Kocher clamp to prevent inadvertent advancement of the K-wire. The pedicle is tapped and the appropriate-size screw placed [Fig. 18.2(e)]. Depending on the system used, the rod attaching the screw heads is placed either on an arc through the muscle tissue (Sextant, Sofamor Danek, Memphis, TN) or down two c-clamp devices (Abbott Spine, Austin, TX) to secure the screw heads. After either system, a final tightening is performed. Since the procedure does not allow open visualization of the rod secured in the screw heads, the rod can inadvertently slip lateral to the screw head before

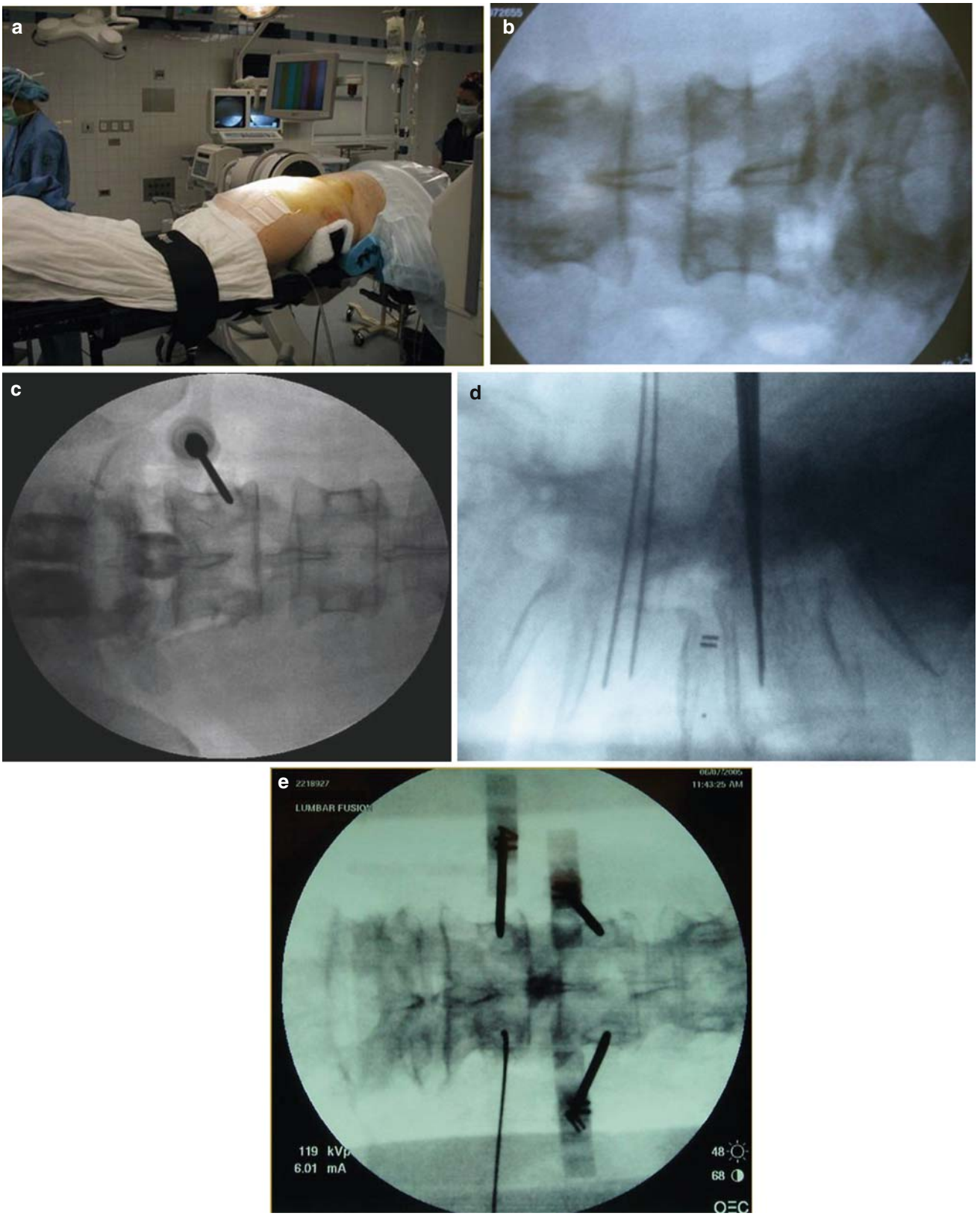

Fig. 18.1 (**a**) Positioning of the patient in the prone position on a Jackson OR table to allow for free movement of fluoroscopic C-arm from anteroposterior (AP) to lateral views for pedicle targeting. (**c**) The targeted vertebra is placed in the center of the fluoroscopic screen with the endplate as a single line and the spinous process between both pedicles. (**c**) The Jamshidi needle is advanced through the pedicle from the facet-transverse process junction to (**d**) the base of the pedicle-vertebral body, making sure not to cross the medial cortical margin of the pedicle and inadvertently enter the spinal canal. (**e**) Multiple Jamshidi needles can be placed to target the pedicles and K-wires placed

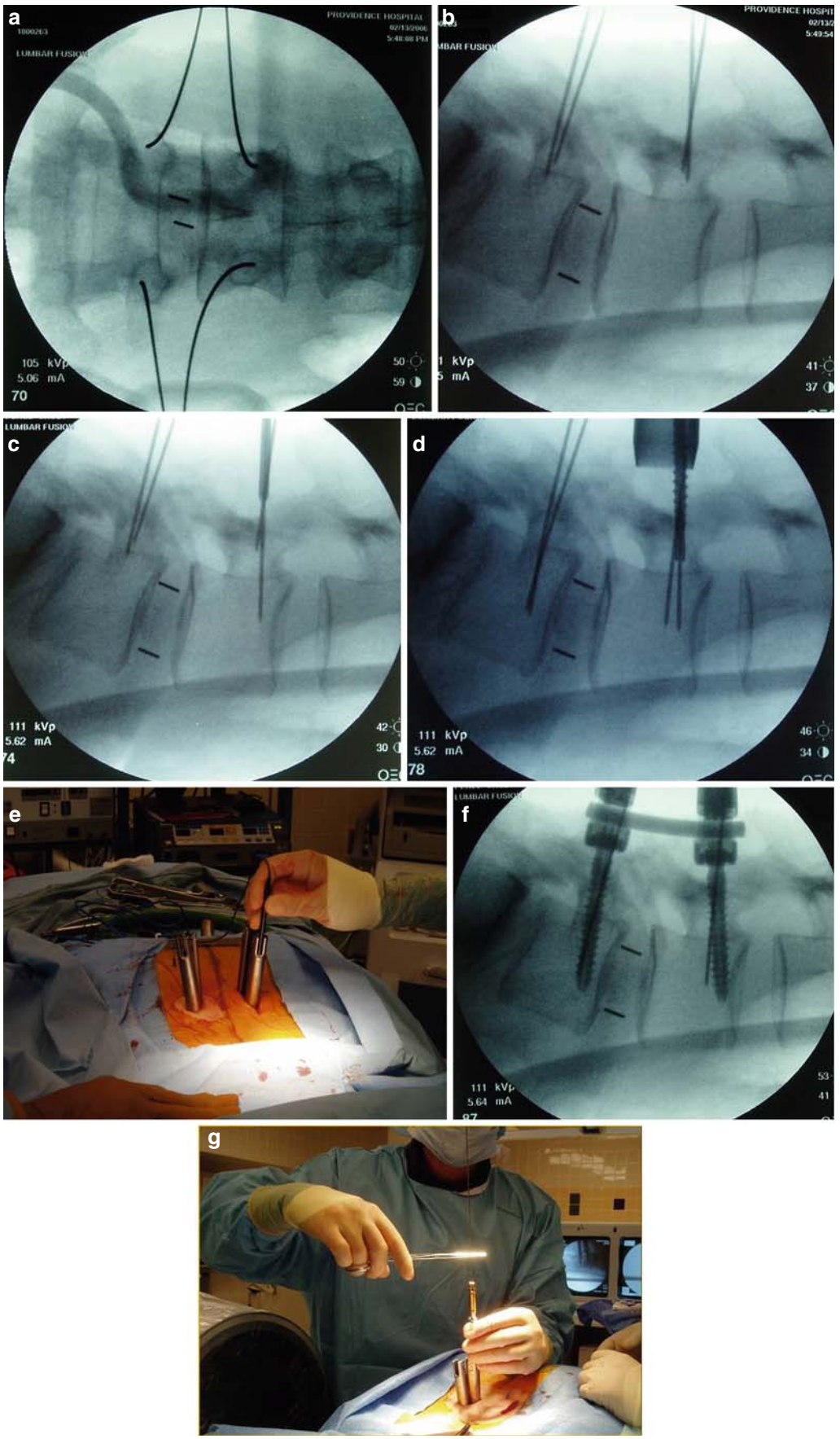

Fig. 18.2 (**a**) Intraoperative AP fluoroscopic image showing placement of K-wires into pedicles using K-wire driver. Note that all K-wires are lateral to the medial border of the pedicles. (**b**) In the lateral fluoroscopic view, the K-wires are (**c**) driven through the pedicles into the vertebral body. (**d**) The pedicle is tapped over the K-wire, and (**e**) pedicle screws are placed, making sure to (**f**) hold the K-wire while placing all cannulated instruments over the K-wire. (**g**) Intraoperative pedicle screw stimulation can improve the safety of placement of pedicle screws

the final tightening. Therefore, it is advised to take another AP and lateral fluoroscopic view before the final tightening of the rod to the screw heads to ensure that the rod is indeed seated properly in the screw heads.

Bull's-Eye Targeting of the Pedicle Screws

Another effective method of targeting the pedicles percutaneously is a technique we call the "bull's-eye" approach [3–5]. The AP view of the pedicle is performed as previously described. A specially made P-C (Perez-Cruet) pedicle access device (Abbott Spine, Austin, TX) is made to dock on the superior articular process of the targeted pedicle [Figs. 18.3((a)–(c)]. The trajectory of the device is then manipulated so that the center of the pedicle is targeted [Figs. 18.1(c), 18.1(d)]. Once in position, a few gentle taps with a mallet secures the device to the superior articular process. Unlike the technique described above, the P-C pedicle access device is not driven through the pedicle: The center trocar of the P-C device is removed, and a K-wire on a driver is used to drive the K-wire into the pedicle partway (about 0.5–1 cm) [Figs. 18.3(d), 18.3(e)]. The P-C device is removed and AP fluoroscopy performed to ensure that the K-wire is properly positioned. If necessary, the K-wire can be easily repositioned. Additionally, it is easy to remove the P-C device without pulling out the K-wire since it is not driven far into the bone. The C-arm is then positioned for a lateral view, the P-C device is placed over the K-wire, and the K-wire is driven into the pedicle to half the vertebral body length. A series of dilators is passed over the K-wire, over which a tubular retractor is placed, and the muscle dilators removed. The pedicle is tapped through the tubular retractor and a screw placed in a similar fashion as described above. Care is taken during passage of any cannulated instrument over the K-wire to hold the K-wire firmly with an instrument to ensure that it does not pass beyond the border of the vertebral body, where it could injure abdominal viscera [Fig. 18.3(e)]. The effectiveness of this technique has been evaluated with postoperative CT images.

A retrospective review of all available postoperative CT scans was undertaken (Fig. 18.4). A prevertebral coronal section was used to categorize the pedicle's location (Table 18.2). A comparison of pre- and postoperative outcomes was subsequently undertaken and used for statistical analysis (χ^2 and T-student). There were 41 patients, 13 male and 28 female, with a total of 164 pedicle screws, 6.5 mm in diameter, with variable lengths. There were 8 pedicle screws in L2, 8 in L3, 26 in L4, 68 in L5, and 54 in S1. Of these screws, 110 were in Grade I, 18 in Grade II, 6 in Grade III, 19 in Grade IV, and 11 in Grade V. There was no statistical correlation between the radiological classification and clinical outcomes. None required immediate postsurgical revision.

Minimally Invasive Instrumentation

One of the goals of instrumentation is to enhance the rate of spinal fusion. The most important determinant of favorable surgical outcome is appropriate patient selection through an understanding of surgical indications [17]. Lonstein et al. [18] described in a retrospective review of the pedicle screw procedures over a 10-year period that, provided the surgeon is experienced and adheres to the principles and details of operative technique, there are few complications. Weinstein et al. [19] compared a more lateral approach with the medial approach of pedicle screw insertion described by Roy-Camille et al. [3] and found it to be more accurate in the lower lumbar spine. However, there is a significantly wide variation in pedicle anatomy among individuals, which can lead to difficulties in the accurate placement of pedicle screws. Davne and Myers [20] noted that in 43 (8.1%) of 533 procedures, the screw placement was difficult or unsatisfactory because of variations in anatomic landmarks, bone density, pedicle size, or disc space penetration.

In a prospective analysis comparing minimally invasive versus open pedicle screw instrumentation, longer operative times were seen in the minimally invasive instrumentation group, although minimally invasive patients showed less operative blood loss, no need for blood transfusions, improved outcomes, and shortened hospital stays [8, 9]. Additional retrospective analysis of a relatively large patient series revealed that the minimally invasive placement of pedicle screws performed by experienced surgeons shows great outcome. Outcomes in patients undergoing minimally invasive fusion and instrumentation revealed an improvement in Visual Analog Scale (VAS) score (from 7.7 preoperatively to 2.89 postoperatively), the Oswestry Disability Index was also reduced (from 44.4 preoperatively to 22.4), and SF-36 scores also improved greatly. Prolo scores were 76.4% excellent, 21.5% good, and 1.96% fair. During the course of the study, no patient returned with transitional syndromes, and the rate of fusion using a TLIF approach was 98% at the one-year follow-up [21].

Muller et al. [22] described the use of multiple portals in a cadaveric study to identify bony landmarks and to test the feasibility of performing endoscopic pedicle screw fixation. Furthermore, Endius (Plainville, MA) developed a system for a single-portal approach for posterolateral

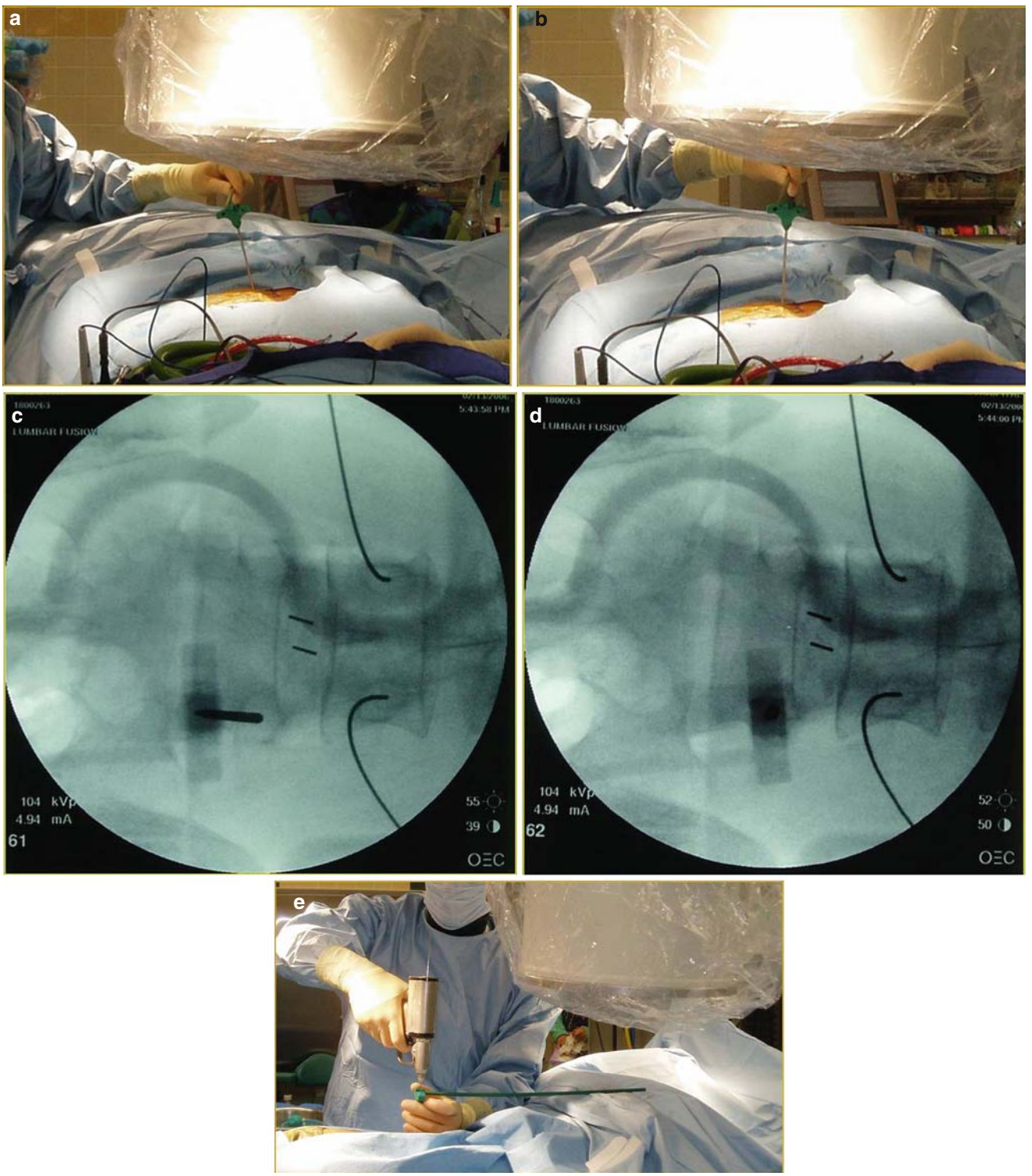

Fig. 18.3 (**a**) The "bull's-eye" technique for targeting pedicle screws is generally used when targeting larger L4, L5, and S1 pedicles. An intraoperative photo shows the "bull's-eye" technique with (**b**) manipulation of the pedicle screw targeting needle (Abbott Spine, Austin, TX). (**c**) The corresponding AP fluoroscopy shows the (**d**) targeted pedicle. (**e**) Since the targeting needle is not advanced through the pedicle, a K-wire driver can be used to drive the K-wire through the pedicle. Efforts are made not to drive the K-wire toward the spinal canal

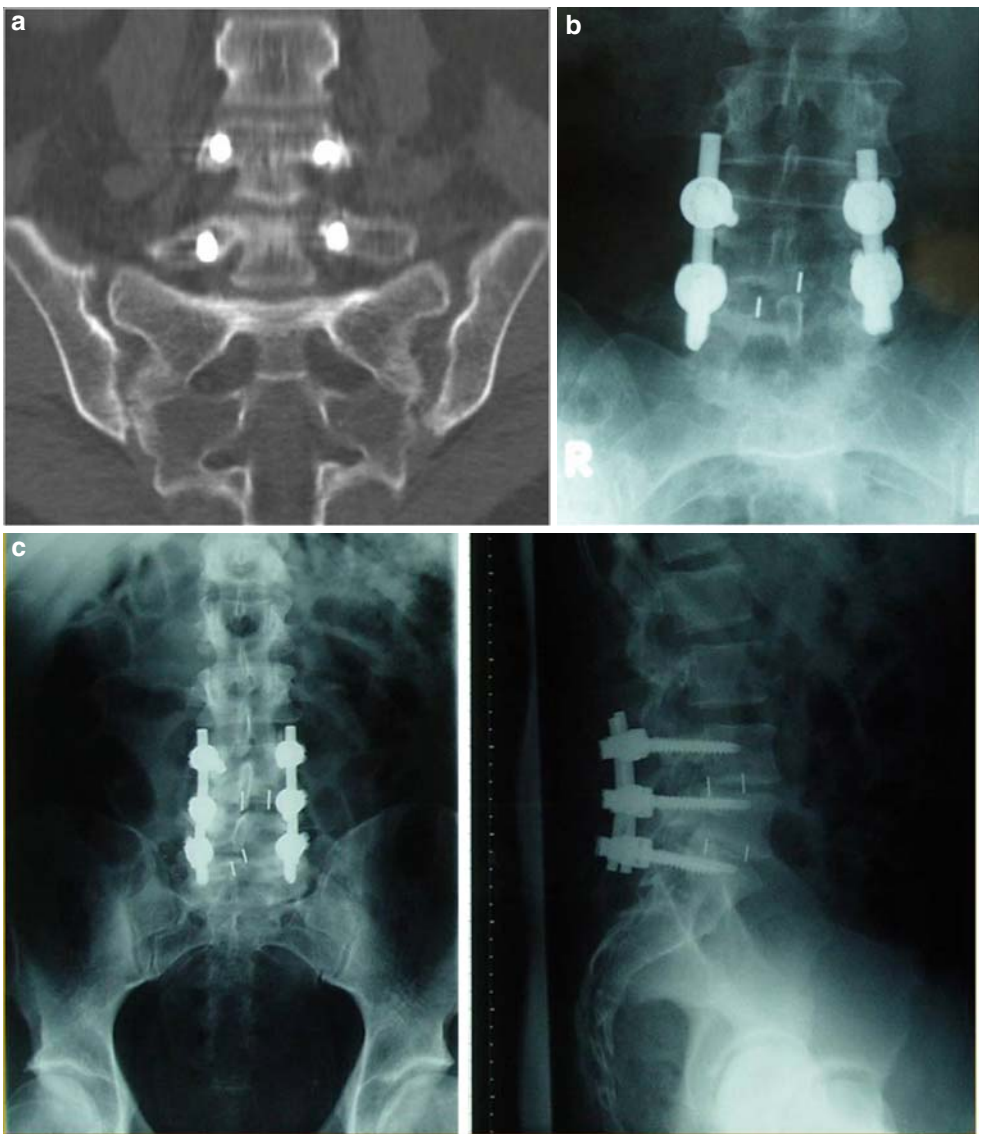

Fig. 18.4 (**a**)–(**c**) Postoperative views after percutaneous pedicle screw placement showing (**a**) CT, (**b**) plain X-rays, and (**c**) multisegmental pedicle screw placement

Table 18.2 Categorization of pedicle location

Grade I: middle third of the pedicle at the center
Grade II: upper third of the pedicle, midline
Grade III: median third of the pedicle, at the center
Grade IV: middle third of the pedicle, lower wall
Grade V: lateral third of the pedicle, at the center

transpedicular screw fixation and posterolateral lumbar arthrodesis. In both approaches, the endoscope is placed over the working area through a transmuscular approach; a biplanar fluoroscope is necessary. By making a small skin incision around the probe, dilators of incremental sizes are passed over the probe until the desired blunt-tipped obdurator can be placed. A rigid operating sheath that measures 1.5 cm in diameter and 5 cm in length is needed to perform this transmuscular insertion approach of the pedicle screw-rod fixation device. The surgical field was further illuminated by an endoscope with a 4-mm diameter, an 18-cm length, and 0°, 30°, and 70° angles. Compared to the PathFinder (Abbott Spine, Austin, TX), which has been used in our series of fusions, the Endius device (Plainville, MA) does not have the k-wire or the Jamshidi needle to access the pedicle. Also, by itself, placement of the rigid operative sheath may cause a greater incision size and may even require more aggressive retraction of the paraspinous muscles, while the tubular retractor used with Abbott Spine's device caused minimal retraction of the muscles, consequently decreasing the morbidity.

Electrophysiological Monitoring

In both of the previously described techniques, electrophysiologic monitoring was used; however, we employed both electromyographic (EMG) and somatosensory evoked potential (SSEP). SSEP has been used extensively in monitoring spinal cord function during spinal deformity correction and decompressive procedures. In this technique, stimulation of a mixed peripheral nerve is monitored at the cortex cerebri. A change in latency of at least 10% or a decrease in signal amplitude of at least 50% is considered significant [23]. This monitoring technique has several shortcomings in relation to monitoring for radicular injury with pedicle screw placement [24]. In SSEP monitoring, the findings are a summated average and therefore not real-time, resulting in a delay in recognizing a potential nerve injury. SSEP monitoring is also not adequately nerve-specific due to the fact that multiple roots are represented in any given peripheral nerve; thus, the nerve roots that are not compromised can hide the response of the damaged root. More important is that monitoring sensory function via SSEPs does not necessarily reflect changes in motor function, which have greater clinical significance [25]. The EMG monitoring of specific muscle groups with dermal or subdermal electrodes allows the specific monitoring of the motor function of individual nerve roots [25]. Owen et al. [24] described the preferred type of monitoring in terms of dynamic and static phases of the spine surgery procedures. The dynamic phases are when decompression, deformity correction, or pedicle hole formation is being performed for pedicle screw placement. The static phase is either before or after a dynamic surgical phase. Continuous, free-running EMG monitoring is most useful in the dynamic phases of the surgical procedure, and evoked-stimulus EMG monitoring is most useful during the static phases of surgery [19, 26–31]. Although this kind of monitoring was initially to assess facial nerve function during posterior fossa surgery, the same technique can be applied for monitoring specific spinal roots during decompressive or spinal instrumentation surgery [32]. Recording electrodes are placed in or over the muscles innervated by the nerve root(s) of interest, and the free-running EMG activity is monitored continuously during the procedure. Normally, the muscles are at rest, although irritated nerve roots in pathologic conditions may exhibit spontaneous EMG activity. This activity is usually a pattern of low-amplitude periodic compound muscle action potentials (CMAP) [33]. Any mechanical deformation of the nerve root will result in the appearance of abnormal potentials. Abnormal, mechanically elicited responses are usually characterized by a burst of high-intensity polyphasic waveforms or a tonic pattern of repetitive synchronous activity [17, 24, 26, 29, 30, 34]. When this activity is seen, the surgeon should respond by stopping what he or she is doing, modifying the technique, or exploring the nerve root in question [21, 24]. Once the pedicle screws have been placed, intraoperative pedicle screw stimulation is performed on each screw. The K-wire can also be stimulated to evaluate proper placement [Fig. 18.2(e)]. If an action potential of 8 mA or less is elicited with screw stimulation, the screw is inspected and repositioned if necessary.

Radiographic Confirmation of Pedicle Screw Placement

The use of spinal instrumentation improves fusion rates in the surgical treatment of chronic debilitating back pain; however, this may or may not correlate with improved clinical outcomes [35]. One of the main difficulties in assessing pedicle screws is having an accurate intraoperative method to confirm pedicle screw placement [17]. Traditionally, screws are placed freehand with the use of anatomical markers [29, 36]. Berlemann et al. [37] found that only 41% of implants were correctly assessed on plain intraoperative radiographs, with an increase to 47% on postoperative films. In comparison to perforations detectable by computed tomography (CT), radiographs missed two thirds of the perforations. Ferrick et al. [38] found that the accuracy of plain radiographs varied from 73-83%, with medial perforations more likely to be accepted as accurate. Farber et al. [39] found 10 times more pedicle violations with CT scanning than with plain radiography. It was of particular concern that this was despite the use of midline laminotomies to palpate the medial wall of the pedicle, which many consider the "gold standard" evaluation of pedicle integrity. These authors found that indirect palpation of the pedicle from a midline laminotomy may not ensure complete accuracy of the pedicle screw placement. Laine et al. [40] found that only 10% of pedicle perforations recognized on CT scans were discovered on plain radiographs. In our analysis, we have found coronal CT scans to be the most accurate at detecting pedicle wall screw breaches (Fig. 18.2).

In an attempt to improve the accuracy of pedicle screw placement, computer-assisted image guidance has been advocated [28]. Laine et al. [40, 41] found an improved accuracy of 95.4% in the computer-assisted group versus 86.6% in the conventional group. The underlying accuracy of the available image guidance technology may, however, be inadequate to place screws successfully at certain spine levels [21].

Therefore, the need for accurate image guidance navigational systems that can assist surgeons in placing pedicle screws accurately is critical [42]. We have found the availability of intraoperative electrophysiological techniques (i.e., intraoperative pedicle screw stimulation) to be extremely helpful in performing safe and accurate percutaneous pedicle screw placement [3, 12, 17, 19, 21, 24, 26, 29, 31, 33, 43–47].

Conclusion

Percutaneous pedicle screw instrumentation can be performed safely and effectively. The benefits to our patients are reduced tissue dissection, reduced blood loss, preservation of normal anatomical supporting structures of the spine, and quicker recoveries. The pedicle offers the strongest site of fixation for spinal instrumentation [14]. Mastering radiographic targeting of the pedicle can be done with a thorough appreciation of the bony anatomy of the spine and those landmarks critical in performing safe and accurate percutaneous pedicle screw placement. In addition, intraoperative percutaneous pedicle screw stimulation seems to reduce approach-related morbidity and, in our studies, was an excellent technique to confirm the adequacy of the screw placement [28].

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Iliac Crest Bone Graft Harvest and Fusion Techniques

19

Jeff S. Silber and Alexander R. Vaccaro

Introduction

Approximately 250,000 bone grafting procedures are performed annually in the United States for spinal surgery. Anterior and posterior autologous iliac crest bone grafts (A/PICG) are commonly used in spinal surgery for spinal reconstruction and to obtain fusion. The clinical outcome of autologous iliac crest bone graft usage is more predictable compared to other grafting materials, including allograft, xenograft, and synthetic materials. The basic principles of an anterior cervical discectomy (ACD) or corpectomy (ACC) and fusion procedure includes decompression followed by restoration of the anterior column with a structural graft to achieve a biologic bony union. A structural cortical autologous bone graft has intrinsic stability and provides support while autologous cancellous bone provides cells and protein important for fusion success and a substrate for osteoconduction. However, it contributes no biologic support or structural stability. Autologous cancellous bone is frequently harvested from either the anterior or posterior iliac crest and is placed either anteriorly in a structural cage or posteriorly along the posterolateral cerical masses or intertransverse processes.

Autologous tricortical AICBGs used in ACDF and ACCF procedures are widely used for this purpose throughout the civilized world. These structural grafts are used to achieve several goals, including load bearing following decompression, reconstitution of spinal alignment (lordosis), and a solid bony fusion. In posterior lumbar intertranverse fusions, a larger amount of bone graft is often needed as compared to a one- or two-level anterior spinal interbody procedure. This often requires significant (>45 cc) cancellous bone harvesting, potentially leading to postoperative donor site morbidity. Even with known morbidities due to its use, superior fusion outcomes using autologous iliac crest grafts have been well documented when compared to allograft or synthetic grafts. This is attributed to its superior osteoinductive and osteoconductive properties. Furthermore, a closer matching of the graft modulus to the host bone is obtained with autologous bone graft sources, which minimizes possible graft subsidence and cutout. An autologous bone graft source also obviates the risk of disease transmission and graft rejection compared to allograft bone.

Unfortunately, harvesting iliac crest bone graft is not without a significant risk of donor site morbidity. Methods to decrease this morbidity have focused on either avoiding autologous graft harvesting or minimizing the amount of procured graft using smaller incisions and preserving as much of the cortical architecture of the native iliac crest. Minimal incision bone graft procurement strategies are primarily designed to minimize soft tissue disruption as well as to preserve as much as possible the cortical boundaries of the iliac crest harvest site. This may improve both short- and long-term outcomes related to bone graft donor site morbidity. This chapter discusses the pearls and pitfalls of harvesting the anterior or posterior iliac crest through various minimally invasive approach strategies.

Anterior Iliac Crest Harvest

The reported fusion rates of noninstrumented one- or two-level ACDF and one-level ACCF procedures using autologous anterior iliac crest bone range from 83-100% [1–6]. The use of anterior cervical plating has increased

J.S. Silber (✉)
Department of Orthopaedic Surgery, Long Island Jewish Medical Center, New Hyde Park, NY 11040, USA; Albert Einstein School of Medicine, Bronx, NY 10461, USA
e-mail: jeffsilber@msn.com

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segmental stability, improved multisegmental fusion rates, and decreased graft dislodgement and collapse [3, 5–7]. Unfortunately, the price paid for the use of autologous bone sources is often the discomfort at the bone graft harvest site, which may be chronic and last for a lifetime, interfering with activities of daily living and requiring chronic medication use. This unfortunate complication may be significant and must be thoroughly explained to the patient prior to the surgical procedure. Other common problems seen with the harvest of anterior iliac crest bone graft include lateral femoral cutaneous nerve injury, iliac wing fracture, and iatrogenic hernia [8–11].

Technique

Autologous AICBG can be harvested from either the right or left iliac crest using a standard anterior approach. For tricortical grafts, after infiltration with 1% lidocaine with epinephrine, a skin incision using either a no. 10 or no. 15 scalpel is made at least 2.5 cm distal to the anterior superior iliac spine (ASIS) and parallel to and just above the anterior iliac crest (Figs. 19.1 and 19.2). This will help to avoid injury to the lateral femoral cutaneous nerve and a future avulsion fracture of the anterior superior iliac spine. The skin incision length is variable based on the size of the graft needed but can be retracted as a mobile window with the use of small retractors. Dissection is carried down to the fascia along the superior border of the iliac crest with the use of electrocautery to avoid bleeding and decrease hematoma formation. Care is taken to incise the fascia while avoiding any muscle disruption (Fig. 19.3). The inner and outer tables of the anterior ilium are exposed by elevating the fascia in a subperiosteal manner starting in the middle of the fascia with the electrocautery, creating a nice fascial sleeve both superiorly and inferiorly for easy closure later. A tricortical bone graft of the appropriate size is measured and cut using an oscillating bone saw (Figs. 19.4-19.6). Once the graft has been removed, bone hemostasis is achieved with usage of any hemostatic agent, such as dry gelfoam or bone wax. If the ends of the graft defects are

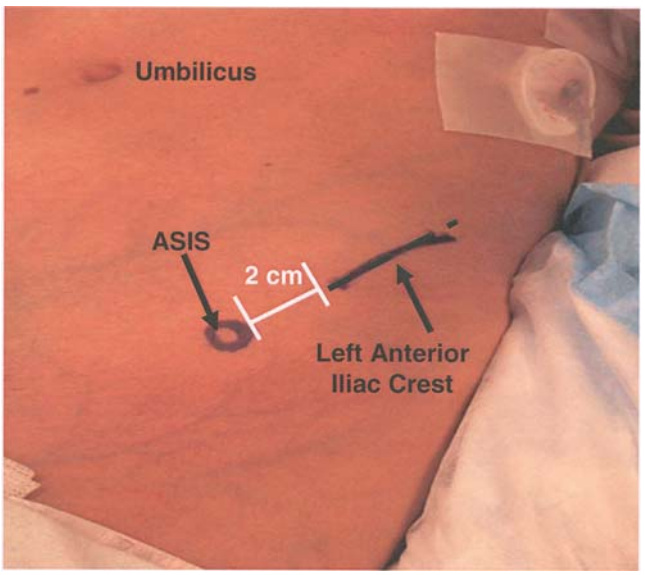

Fig. 19.1 Left anterior iliac crest minimally invasive incision (ASIS: anterior superior iliac spine)

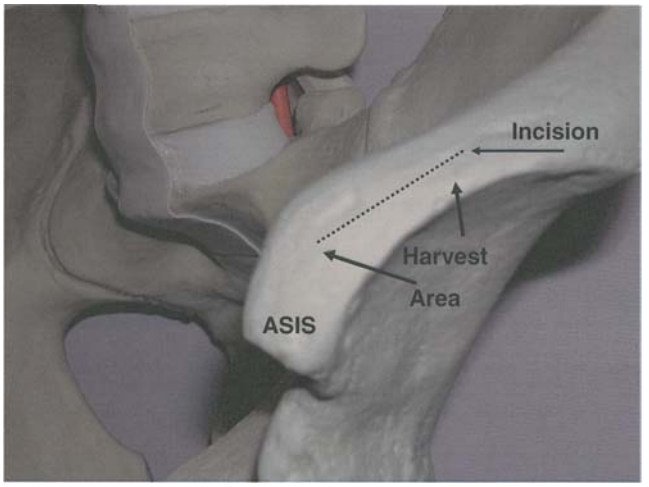

Fig. 19.2 Left iliac crest cadaveric specimen showing appropriate area for incision for graft harvest (ASIS: anterior superior iliac spine)

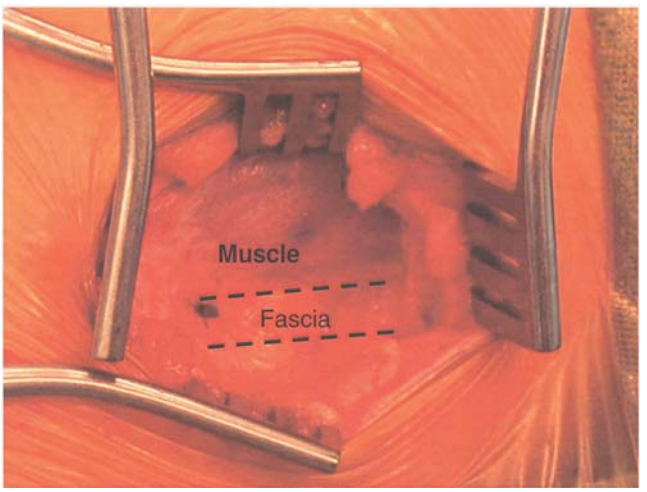

Fig. 19.3 Dissection down to the fascial layer showing muscle above and below

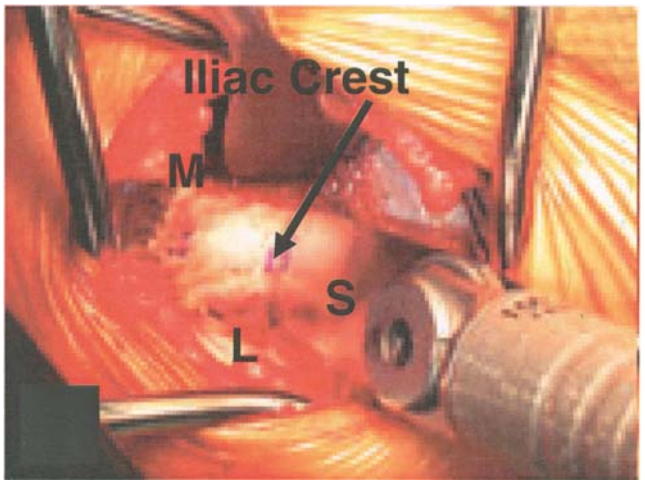

Fig. 19.4 Iliac rest bone exposed with oscillating saw. Retractors are placed along the inner and outer tables of the ilium

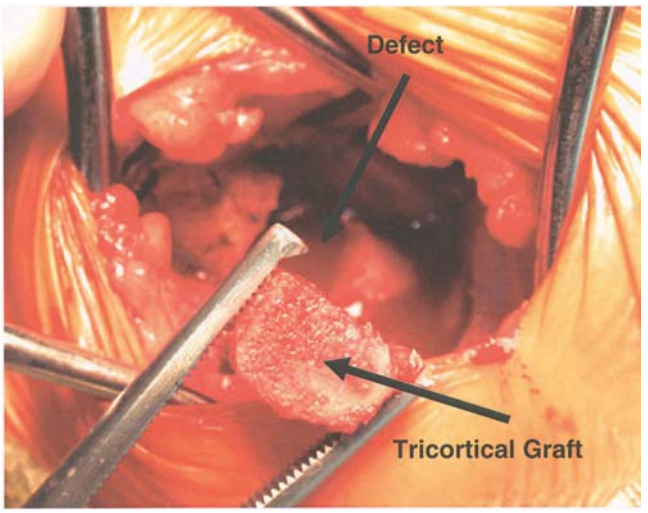

Fig. 19.6 Tricortical bone graft harvested. Defect shown after graft harvest

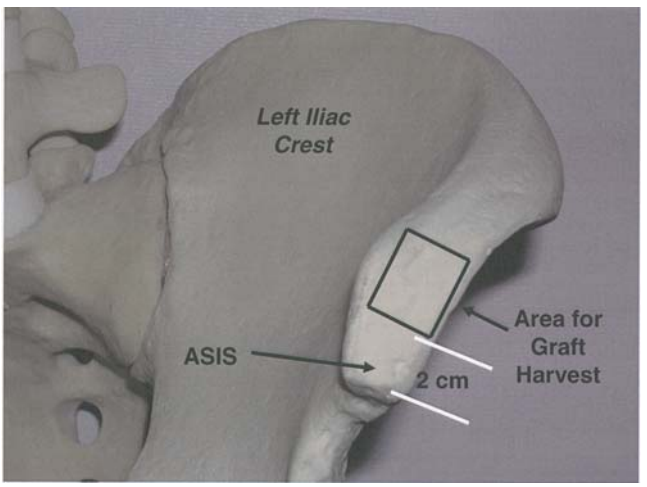

Fig. 19.5 Left iliac crest cadaveric specimen showing appropriate area for graft harvest (ASIS: anterior superior iliac spine)

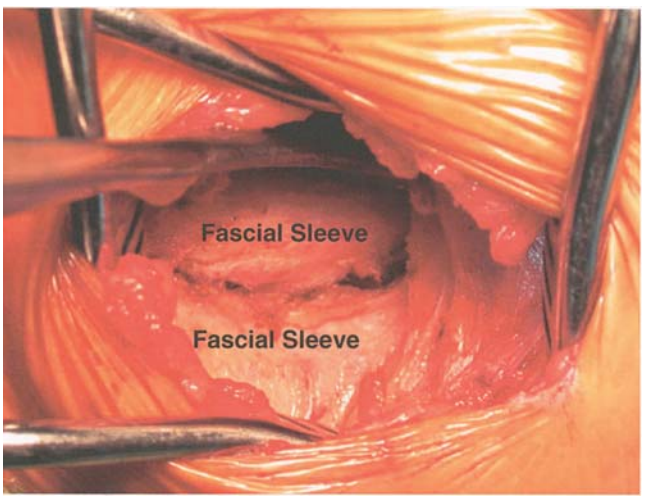

Fig. 19.7 Approximation of the fascial sleeves for closure after bone graft harvest

prominent, as seen with thinner patients, a rongeur can be used to round off the edges (Fig. 19.7). The medial and lateral periosteum and fascia of the abdominal muscles are repaired over the defect using no. 1 Vicryl. The subcutaneous tissue is approximated with 2.0 Vicryl sutures and the skin incision is closed with a running 3.0 absorbable Monocryl or 5.0 Prolene pullout subcuticular suture followed by steri strips and a sterile dressing. 0.5% Marcaine without epinephrine may be injected into the skin edges for postoperative pain relief. Often, iliac crest bone graft harvesting is performed following the initial neck incision and cervical exposure while waiting for development of the intraoperative marker lateral cervical spine radiograph. If only cancellous bone is needed for placement into an anterior fusion device (cage) during an anterior lumbar interbody fusion (ALIF) procedure, the incision can be made smaller and the iliac crest can be opened using either a rongeur or a ¼-in. curved osteotome, followed by curetting the cancellous bone from within the inner and outer tables, followed by replacement of the cortical cap if able. Alternatively, this approach can be performed through a smaller skin incision (16–24 mm) with the use of a minimally invasive surgery (MIS) dilation/retractor system. This MIS technique works well when cancellous graft is needed for interbody cages for ALIF procedures. After an initial small skin incision, gradual soft tissue dilation can be performed onto the iliac crest prior to bone graft harvest. Once the graft has been obtained, the retractor system is removed and closure is as stated.

Common short-term complications at the harvest site of this technique include (1) persistent wound drainage, (2) infection, (3) wound dehiscence, (4) difficulties with activities from pain, and (5) lateral femoral nerve injury with neuroma formation. Long-term complications include (1) chronic harvest site pain requiring pain medication, (2) abnormal parasthesias or numbness at the graft harvest site, (3) discomfort from clothing rubbing against the harvest site, and (4) decreased activities due to pain [11].

Posterior Iliac Crest Bone Grafting

Posterior iliac crest bone graft (PICBG) harvesting differs from anterior graft harvesting, as it usually consists of only nonstructural corticocancellous bone graft. The harvested bone can consist of either cancellous-only or a combination of both cortical and cancellous bone graft. In posterior lumbar intertransverse fusions, it has been well documented that autograft is the gold standard for fusion healing. Unfortunately, this technique is associated with donor site morbidity, with chronic pain being the most commonly reported long-term complication. The authors describe a more minimally invasive technique to harvesting posterior iliac crest autograft while still obtaining an adequate amount of graft material. Complications specifically associated with a posterior iliac crest harvest include injury to the cluneal nerves, superior mesenteric vessels, and penetration into the sacroiliac joint, but as with AICBG harvest, the most common long-term complication is related to chronic pain [11, 12].

Technique

Autologous PICBG can be harvested from either the right or left side using a straight or slightly oblique incision along the posterior superior iliac spine (PSIS). The cluneal nerves cross the iliac crest about 8 cm from the posterior superior iliac spine, and the incision should not extend too far laterally, to avoid inadvertent injury to these superficial sensory nerves. After infiltration with 1% lidocaine with epinephrine, a skin incision is made using either a no. 10 or no. 15 scalpel. The length of the incision is approximately 2–4 cm directly over the posterior superior iliac spine (Figs. 19.8-19.10). There is an internervous plane directly over the PSIS, as no muscles cross the crest at this location. The gluteus muscles originate from the outer ilium or table, and the paraspinal musculature and the latissimus dorsi originate from the inner ilium or table. The skin incision can be retracted as a mobile window with the use of small retractors.

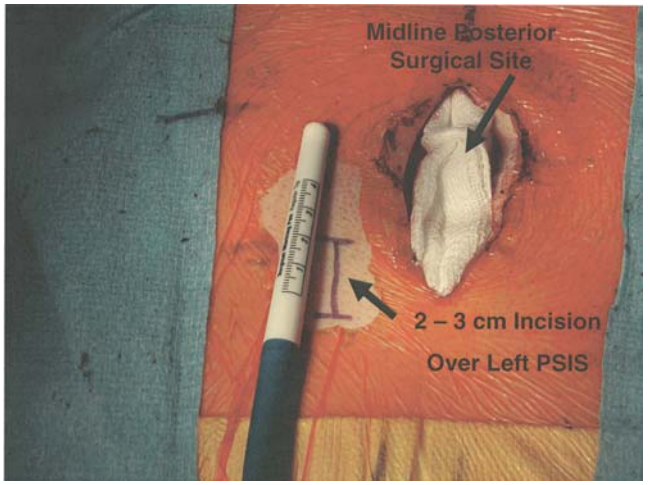

Fig. 19.8 Incision drawn for a left posterior iliac crest harvest

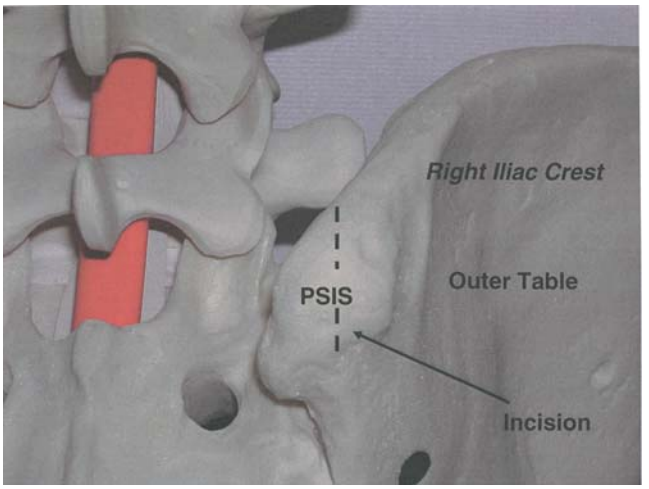

Fig. 19.9 Cadaveric specimen showing incision over the posterior superior iliac spine (PSIS) of a right iliac crest harvest

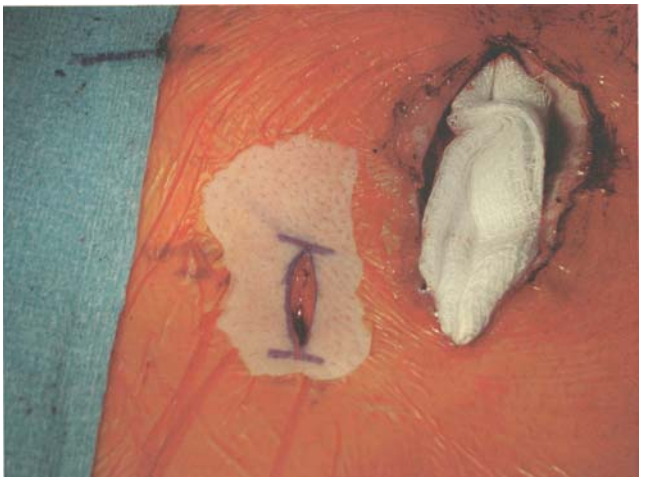

Fig. 19.10 Skin incision to subcutaneous fat and down to fascia

Dissection is carried down to the fascia directly over the PSIS with the use of electrocautery to avoid bleeding and decrease hematoma formation. Care is taken to incise the fascia only while avoiding any muscle disruption. Next, the inner and outer tables of the posterior ilium are exposed using subperiosteal dissection starting in the middle of the PSIS with electrocautery, creating two thick fascial sleeves both superiorly and inferiorly for easy closure later. A ¼- to 1/2-in. curved osteotome is used to remove the cortical cap from the PSIS hinging on the medial cortex for replacement later, or it can be removed and morselized and used as cortical graft (Fig. 19.11). Once the cap of cortical bone has been osteotomized, a good cancellous surface is now available for harvesting (Fig. 19.12). A large curette is used between the outer and inner tables of the ilium in a scooping and rotating fashion, removing adequately sized cancellous graft material (Figs. 19.13 and 19.14). Attention is paid to avoiding penetration of the inner ilium table with subsequent sacroiliac joint penetration and the outer ilium table with injury to the gluteal musculature. After the desired amount of graft has been harvested, replacement of the cortical cap is performed if it has not been used for graft material (Fig. 19.15). After irrigation, hemostasis is achieved with either dry gelfoam or bone wax. The medial and lateral periosteum and fascia of the abdominal muscles are repaired over the defect with no. 1 Vicryl (Fig. 19.16). The subcutaneous tissue is approximated

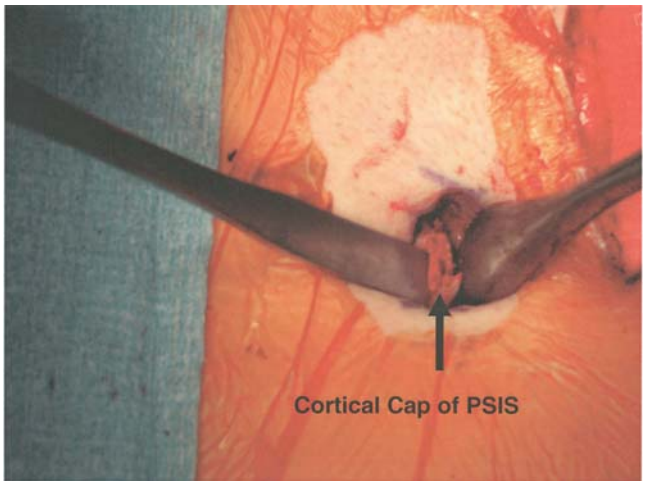

Fig. 19.11 PSIS exposed with curved osteotome removing the cortical cap (PSIS: posterior superior iliac spine)

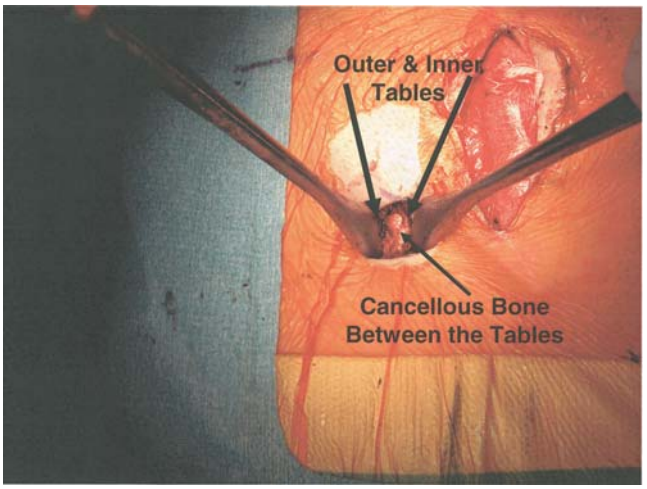

Fig. 19.12 Cortical cap has been removed, exposing cancellous bone between the inner and outer tables

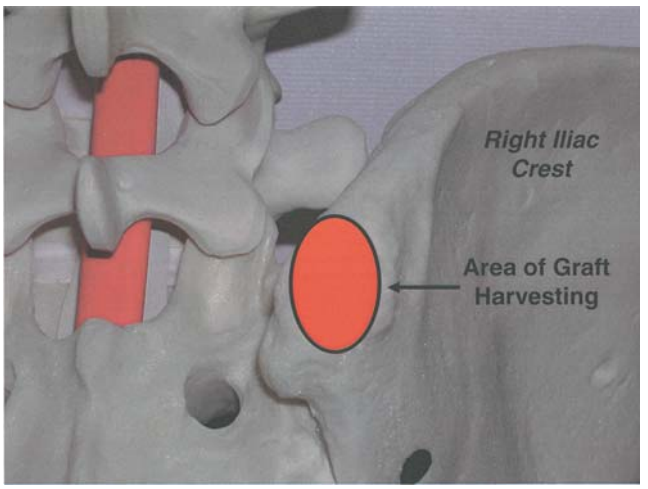

Fig. 19.13 Cadaveric specimen showing the area of a right graft harvest between the ilium tables

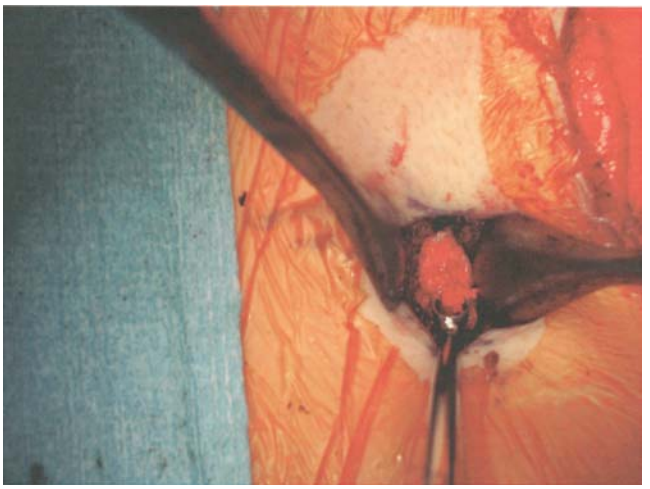

Fig. 19.14 Harvesting of the cancellous bone with a large curette between the tables

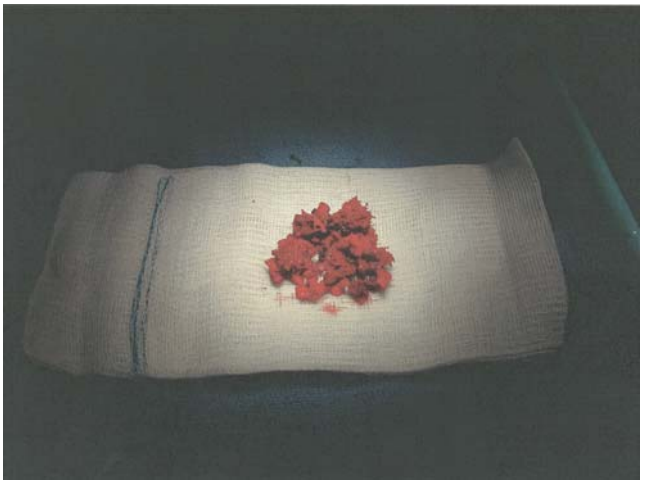

Fig. 19.15 Bone graft harvested for a posterolateral fusion and for intervertebral cage packing

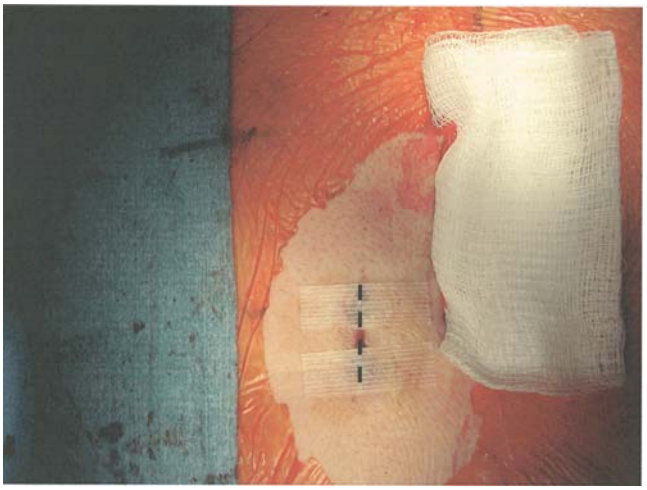

Fig. 19.16 Closed minimally invasive incision with steri strips applied

with 2.0 Vicryl sutures, and the skin incision is closed with a running 3.0 absorbable Monocryl subcuticular suture or staples followed by steri strips and a sterile dressing. 0.5% Marcaine without epinephrine is infiltrated into the skin edges for postoperative pain relief. We recommend harvesting the iliac crest graft at the time of graft placement in order to ensure as much graft osteoprogenitor cell survival as possible. If only a small amount of cancellous bone is needed for placement into an interbody fusion device, the incision can be made smaller and the iliac crest can be opened using either a narrow rongeur or a ¼-in. curved osteotome followed by the technique previously described. Obtaining large amounts of corticocancellous strips from the outer table cannot be harvested through a minimally invasive approach and will not be discussed in this chapter, although a large amount of graft material can be procured through the minimal access approach explained above.

Common short-term complications of this technique include (1) persistent wound drainage, (2) infection, (3) wound dehiscence, and (4) difficulty with activities from pain. Long-term complications include (1) chronic harvest site pain requiring pain medication, (2) abnormal parasthesias or numbness over the buttocks from cluneal nerve injury, and (3) sacroiliac joint pain from inadvertent instrumentation penetration.

Discussion

The basic principles of a biologic fusion procedure include the presence of a biologically compatible bone graft, which has the ability, if necessary, of providing structural support (ACDF and ACCF) as well an osteoconductive/osteoinductive matrix to assist in fusion healing and maturation (ACDF, ACCF, posterolateral intertransverse process). The theoretical advantages of using autologous bone graft include higher fusion rates while avoiding the risk of disease transmission. Although the use of autologous iliac crest is still the gold standard, donor-site morbidity is always a significant drawback to this technique. With minimizing incisions, soft tissue dissection, and using bony windows to preserve the overall bony architecture, the overall morbidity of autologous bone graft harvesting may be significantly reduced. Even so, surgeons should advise their patients of the potential long-term functional impairments that may be associated with this portion of the procedure.

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Technologies for Use in Indirect Distraction Procedures

20

Hansen A. Yuan, Adam K. MacMillan, and Edward S. Ahn

Introduction

Osteoporosis results in the thinning of the cortical shell and trabecular struts of the bones such that the loads of normal daily activities can result in fractures. In the case of osteoporosis of the vertebrae, vertebral compression fractures (VCF) can occur spontaneously or as the result of a low-energy trauma, resulting in chronic pain and reduced mobility [1]. If left untreated, multiple VCFs can result in chronic pain, loss of height, and spinal deformity. More importantly, VCF incidence has been increasing with the associated aging of the demographic. Furthermore, there are approximately 440,000 VCFs per year in Europe, resulting in a direct annual cost of $440 million, and 700,000 VCFs per year in the United States, resulting in a direct annual cost of $750 MM [2–5].

In response to this clinical need, Galibert and Deramond performed the first percutaneous vertebroplasty (VP) in 1984 [6]. In this procedure, polymethylmethacrylate (PMMA) was injected under high pressure into the vertebral body to distract the vertebra and to improve the structural integrity, alleviating pain. Kyphon, Inc. further optimized vertebroplasty by promoting the use of an inflatable bone tamp to indirectly distract the vertebra to facilitate a low-pressure injection of PMMA, restoring kyphosis; this procedure is now known as kyphoplasty. In both vertebroplasty (VP) and kyphoplasty (KP), the objective is to augment the weakened vertebral body to relieve pain.

While VP and KP have solved the challenges associated with percutaneous delivery and instrumentation for the indirect distraction of vertebral compression fractures, the use of PMMA limits the use of indirect distraction procedures to older patients. PMMA is still the only cement cleared for use in VP and KP in the United States although calcium phosphate cements (CPC) are being used outside the United States (OUS). In general, indirect distraction procedures are well tolerated with a low incidence of complications; however, when complications do occur, they can be fatal. Due to the fragmentation of the vertebral body, extravasation of the PMMA or CPC is the primary concern. Cement extravasation is a frequent occurrence in vertebroplasty, occurring in 38–72.5% of cases [7–9]. Extravasation into soft tissue occurred at 6–53%; into the spinal canal at 38%; into the intervertebral disk at 5–25%; into prevertebral veins at 5–17%; and into epidural veins at 16.5% [10]. Cement emboli are frequent but are usually asymptomatic [11]. However, in certain cases, fatalities can occur [12]. Cement can also leak into the epidural and disc space or through the endplates. Leaks into the epidural space can cause spinal cord compression, resulting in additional surgery to avoid neurological complications. Leaks into the disc spaces and paravertebral soft tissues are without clinical consequence, whereas leaks into the endplates have been associated with a higher risk of adjacent vertebral collapse.

In this chapter, we review the performance of these cements in indirect distraction procedures. Numerous authors have provided an excellent summary on this topic and have summarized the desirable properties for injectable cements for use in VP and KP indications [13–16]. These properties can be categorized as *handling and setting*, *mechanical and biomechanical,* and *in vivo* characteristics. The cements' behavior and response are reviewed in this chapter. We also discuss near-term and future technologies that will have an impact on this indication.

H.A. Yuan (✉)
Department of Orthopaedic and Neurologic Surgery, State University of New York-Syracuse Medical Center, Syracuse, NY 13202, USA
e-mail: yuanh@upstate.edu

Polymethylmethacrylate Cement

While clinical outcomes with PMMA in indirect distraction procedures have been excellent [13], the nature of the

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material is such that the palliative effects achieved with using PMMA relative to the potential risks are favorable only with a carefully selected group of patients, the elderly osteoporotic patient. These risks are primarily related to material properties such as handling, setting, and in vivo behavior.

Handling and Setting Characteristics

During the early history of VP, the handling and setting characteristics of the original PMMA bone cements were found not to be well suited for VP. PMMA typically has a setting time of approximately 8 min, depending on the ambient temperature. A majority of this time, PMMA maintains a constant viscosity. During the first 30–50 s after mixing, the material has a very thin consistency; this viscosity, however, is too low for injection, as extravasation is likely to occur. As polymerization of the methacrylate monomer occurs, the molecular weight of PMMA increases such that the cement becomes significantly more viscous. At this point, it can be injected with a reduced risk of extravasation. However, the transition from a workable viscous condition to an unworkable set condition occurs very quickly; this behavior is often described colloquially as "snap set." Consequently, the window for injection is relatively narrow.

The early practitioners of VP, consequently, adapted commercially available PMMAs used in cemented arthroplasties such as Simplex® P, Osteopal®, and Palacos® for their specific needs by adjusting the powder-to-liquid ratio to obtain the appropriate "feel."They increased the monomer-to-polymer ratio above the recommended ratio (typically, 0.5 ml of monomer/g of PMMA solids) to obtain longer setting times and to decrease the viscosity to improve the injectability [8, 17, 18]. As a result of these changes, the mechanical strength of the PMMA decreased [18, 19]. However, we believe this reduced strength should not affect the functional clinical outcome since palliative effects are also achieved with CPC, a much weaker material than PMMA.More importantly, traditional PMMA cements were not sufficiently radiopaque for an image-guided procedure such as VP or KP, and radiopacifiers were incorporated to improve visualization.Cements were often loaded with up to 20–30 wt/wt% of $BaSO_4$ and/or 1–5 g of either tantalum or tungsten powder [16]. Currently, vertebroplasty cements utilize up to 30 wt/wt% of $BaSO_4$ or ZrO_2, as shown in Table 20.1.Similar to increasing the monomer-to-polymer ratio, the additional radiopacifier was shown to decrease the strength and fatigue life [20]. Again, this ought not to affect the functional clinical outcome.Finally, the number of residual unreacted monomers in the set cement increased, resulting in a higher risk of arterial hypotension, cardiac dysfunction, or neurological dysfunction [18, 19].

The handling properties of VP, as previously stated, had required changes in the PMMA formulation to lower the viscosity, increase the setting time, and increase the radiopacity relative to the PMMA bone cements used in total joint replacements.There are now new "ready-for-use" PMMA cements for vertebroplasty, such as

Table 20.1 Vertebroplasty PMMA cements

Manufacturer	Product name	Radiopacifier	Powder	Monomer	Promoters; initators
Advanced Biomaterial Systems, Inc.	Symphony™ VR Radiopaque	28 wt/wt% $BaSO_4$	71.3 wt/wt% Polymethylmethacrylate-co-styrene	Methylmethacrylate	Dimethyl-p-toluidine; benzoyl peroxide
DePuy Spine; DePuy CMW	Vertebroplastic™ Radiopaque Bone Cement	28.6 wt/wt% $BaSO_4$	56.8 wt/wt% Polymethylmethacrylate; 14.2% wt/wt% methylmethacrylate-co-styrene	Methylmethacrylate	Dimethyl-p-toluidine; benzoyl peroxide
Kyphon, Inc.	KyphX® HV-R™	30 wt/wt% $BaSO_4$	68 wt/wt% Polymethylmethacrylate-co-styrene	Methylmethacrylate	Dimethyl-p-toluidine; benzoyl peroxide
Heraeus Kulzer GmbH	Osteopal® V	33 wt/wt% ZrO_2	40 wt/wt% Polymethylmethacrylate-co-styrene	Methylmethacrylate	Dimethyl-p-toluidine; benzoyl peroxide
Stryker	Spineplex®	30 wt/wt% $BaSO_4$	69.1 wt/wt% Polymethylmethacrylate-co-styrene	Methylmethacrylate	Dimethyl-p-toluidine; benzoyl peroxide

Osteopal® V (Biomet Merck) and Vertebroplastic®(-Johnson and Johnson®), which allow safer injections by eliminating excessive manipulation of the cement, as shown in Table 20.1. The handling and setting properties for KP are slightly different from VP due to differences in the procedure.Since KP uses an inflatable tamp to prepare the vertebra prior to injection, Kyphon's kyphoplasty cement, Kyphx HV-R, has an increased solids fraction to increase both the viscosity and radiopacity. While the biocompatibility and exothermic reaction of PMMA are its major drawbacks, these do not seem to be major problems given the positive clinical results and the generally small volumes injected.

As previously stated, the majority of complications are related to extravasation, which is a direct consequence of the handling and setting properties of PMMA. While most cases of cement extravasation are minor, the potential for serious complications and death does exist. For example, Chung et al. observed an embolism in the bilateral renal fossae after an 8-ml unipedicular injection [21]. Nussbaum et al. determined that 58 reports were filed, including eight deaths, from 1999 to 2003. Cases included anaphylactic reaction to the bone cement resulting in cardiac arrest, breach of posterior wall resulting in cement extravasation, and cord compression [22]. Monticelli et al. reported that the average volume of cement injected ranged from 5.4 to 7.1 ml and that the majority of complications were as a result of leakage into the spinal canal or the perivertebral venous system [12]. In their case, Monticelli et al. reported that 15 ml of PMMA was injected after which the patient died from grave acute pulmonary embolism. Forensic autopsy revealed that the cement completely filled both the left and right pulmonary arteries.These complications are a direct result of the handling properties of PMMA. In order to minimize extravasation, optimization of the viscosity is critical. Cements with higher viscosities are preferred; shear thinning or thixotropic characteristics would be ideal.

Mechanical and Biomechanical Performance

The biomechanical performance of cement in an indirect distraction procedure is dictated by the mechanical properties of the cement itself, the volume of cement injected, and the distribution of the cement in the vertebrae. Several researchers have evaluated the effect of PMMA injection on the strength and stiffness of a fractured vertebra. Liebschner et al. performed an interesting study investigating the effect of cement volume on the stiffness of a vertebral body using a finite element analysis. Though theoretical, they concluded that only 15 percent vol, or 3.5 ml, was needed to restore stiffness after a compression fracture.Greater volumes resulted in stiffnesses greater than the intact level. Furthermore, overfilling or asymmetric filling may not result in an optimal biomechanical configuration [23]. Belkoff et al. performed a study with similar objectives in an ex vivo cadaver spine bipedicular VP biomechanical model to examine the dose response with respect to strength and stiffness restoration. The authors demonstrated that while only 2 ml was needed to restore strength, 4 ml was needed to restore stiffness in the thoracic region and 6 ml in the lumbar region [24]. Consistent with these results, Ryu et al. achieved pain reduction with as little 3 ml clinically [25]. In addition, an injection of 2.5–4 ml of PMMA into the vertebral body also resulted in pain relief in patients with osteoporosis and symptomatic hemangioma [26, 27].

There has been much discussion in the literature as to the mechanism of action and whether the palliative effects are a result of the increased stiffness or strength of the treated vertebral body. Given the small amount of cement injected, the stiffness and strength of the vertebral body may not be altered significantly. Thus, the analgesic effect cannot be explained by the consolidation of the pathological bone by the cement alone. In the cases of low-volume PMMA injection, the consolidation effect is likely to be minimal. If only a small volume of PMMA is needed to achieve an analgesic effect, it is likely that only a local increase in stiffness may be needed to relieve the relative motion between fragments. The segments no longer have the mobility to impinge on a nerve, and the restrained vertebra does not progressively undergo fracture, reducing the release of inflammatory cytokines, thereby reducing pain. Consequently, stronger or stiffer cement may permit a smaller-volume injection to achieve a palliative effect.

In vivo Behavior

Though PMMA has been well tolerated in VP and KP, there are three major concerns associated with PMMA. The first concern is the high-polymerization isotherm. During the polymerization of PMMA, the temperature of the cement ranges from 80-120°C.This can lead to thermal necrosis of the soft tissues at the augmentation site. Moreover, this exothermic reaction could potentially damage adjacent tissues in the case of cement leakage. The second concern is the toxicity of the monomer. As a result, the residuals could lead to chemical necrosis and vasodilatation [28]. The third concern is the lack of reactivity of PMMA in regards to bone formation.

Nonetheless, PMMA has been clinically effective despite these concerns.Fessl et al. reported that vertebroplasty was very successful. Pain decreased by 70% within three months, and quality of life increased for 92% of patients by six months and 100% by 12 months. However, leakage was observed in 20% of the cases, and additional vertebral fractures were observed during follow-up [29]. Martin et al. treated 40 patients in 68 levels with vertebroplasty for four years with good success.The authors used a diluted mixture of Simplex P (Stryker) to extend the working time to 8 min and added 1 g of tungsten powder (Nycomed) to enhance the radiopacity. They achieved an overall success rate of 80% and a complication rate of 6% per level. Most complications were related to excessive PMMA leaking toward the epidural vein and close to the foraminal segment of the nerve roots, reiterating the need for cement with better handling properties [30].

Calcium Phosphate Cements

Calcium phosphate cements (CPC's) are among the most biocompatible cements available to surgeons and possess the additional benefits of superior osteoconductivity and resorbability; a list of commonly available CPCs is provided in Table 20.2.The composition of CPCs inherently makes them the most "bone-like" cement and could avoid the problems of toxicity associated with PMMA, allowing indirect distraction procedures to be more aggressively performed on younger patients who could benefit from the osteoconductive and resorbable properties. However, CPCs possess several drawbacks: poor strength, poor handling characteristics, and long set times. Furthermore, CPCs have only been approved in the United States for nonload-bearing applications such as cranial defects; no CPC has been approved for use in VP and KP in the United States. Finally, the use of CPCs in VP and KP has resulted in several negative clinical outcomes.

Calcium Phosphate Cement Chemistry

Monma and Kanazawa reported on CPCs based on upon α(alpha)-TCP as early as 1976, but its high curing temperature (80°C) and long curing time (2 h) rendered it impractical [31]. It was not until Chow and Brown proposed a formulation based upon a mixture of basic tetra-calcium phosphate [TTCP; $Ca_4(PO_4)_2O$] and acidic brushite (dicalcium phosphate dihydrate; DCPD; $CaHPO_4 \cdot 2H_2O$) or basic TTCP and acidic monetite (dicalcium phosphate anhydrous; DCPA; $CaHPO_4$) that CPCs had the potential to be clinically useful [32].

Table 20.2 Calcium phosphate cements

Manufacturer	Product name	Cement type	Basic CaP	Acidic CaP	Other additives	Liquid
Biomet Europe	Calcibon®	CDHA	α-TCP	DCP	Calcium arbonate; PHA	
ETEX	α-BSM	CDHA	ACP	DCPD		0.9% NaCl
Lorenz Surgical	Mimix	HA	TTCP	α-TCP		Citric acid
Merck/ Biomet	Biocement D	CDHA	α-TCP	DCP	Calcium carbonate; PHA	
Mutsubishi Materials Co., Saitama, Japan	Biopex R	CDHA	75% α-TCP 18% TTCP	5% DCPD	2% HA; chondroitin sodium sulfate	Sodium succinate
Stryker	Hydroset™ Injectable HA Bone Substitute	HA	TTCP	DCP	Tri-sodium citrate	Sodium phosphate; polyvinylpyrrolidone; water
Stryker	BoneSource® BVF	HA	72% TTCP	28% DCP		0.25 mol/l Sodium monophosphate
Synthes	ChronOS Inject™	Brushite	42 wt.% β-TCP 3 wt.% β-TCP granules	21 wt.% MCPM		5 wt% Magnesium hydrogen phosphate < 1 wt% sodium hydrogen pyrophosphate; magnesium sulfate
Synthes	Norian®SRS®	CDHA	α-TCP	MCPM	Calcium carbonate	

CDHA, calcium-deficient hydroxyapatite; DCPD, dicalcium phosphate dihydrate; HA, hydroxyapatite TCP, tricalcium phosphate; TTCP, tetracalcium phosphate; HA, hydroxyapatite; DCP, dicalcium phosphate; MCPM, monocalcium phosphate monohydrate.

TTCP is an especially important reactant for CPCs since it is the most basic soluble calcium phosphate and the only calcium phosphate with a calcium-to-phosphate ratio of 2, greater than 1.67, the calcium-to-phosphate ratio of hydroxyapatite. DCPD and DCPA are primarily selected because their solubility isotherms intersect near a pH of 8. Alpha tricalcium phosphate [α(alpha)-TCP; α(alpha) $Ca_3(PO_4)_2$] is the second-most basic calcium phosphate but has a calcium-to-phosphate ratio of only 1.5. TTCP can be formulated with DCPD or DCPA such that the calcium-to-phosphate ratio of all the reactants is 1.67, to achieve a stoichiometric HA cement product. In the case of α(alpha)-TCP and DCPD or DCPA formulations, non-stoichiometric HA cements products are formed. These basic calcium phosphates form the backbone of all CPCs.

Whereas the free radical polymerization used to set and cure PMMA is relatively straightforward, CPC set and curing reactions are more nuanced and easily affected by physiological conditions. Typically, CPCs are prepared by mixing a powder containing a mixture of calcium phosphates with an acidic aqueous accelerator such as sodium hydrogen phosphate (Na_2HPO_4). The powder-to-liquid ratio is typically 0.5 g/ml and dictates both the mechanical strength and injectability. While higher powder-to-liquid ratios are required for strength, lower ratios are needed for injectability.

Regardless of the ratio, the setting and curing of CPCs involve the dissolution of the calcium phosphate powders in the liquid accelerator and the subsequent reprecipitation of crystals of the cement product. The cement is considered "cured" when the cement crystals have sufficiently grown to be mechanically entangled with each other; the resulting rise in mechanical strength is proportional to the degree of crystal entanglement. The first step in forming CPCs occurs with the dissolution of various acidic and basic calcium phosphate salts at physiological conditions. Dissolution occurs when the surrounding environment is undersaturated with respect to the product phase (i.e., hydroxyapatite) and continues until the pH and solution composition reach a singular point where the acidic and basic calcium salts are in equilibrium with the solution. However, these calcium and phosphate ions in solutions are supersaturated with respect to the least-soluble phase of calcium phosphate for a given pH, and as a result, the least-soluble calcium phosphate phase begins to precipitate. As the calcium and phosphate ions are depleted from solution with the formation of the least-soluble phase, the reactants undergo additional dissolution to maintain saturation until all the reactants have been consumed.

In the case of most CPCs, hydroxyapatite is the least-soluble calcium phosphate to precipitate. The chemistry of the cement product can be adjusted with changes in (1) the acidic and basic calcium phosphates in the raw material, (2) pH during precipitation, and (3) additives. For example, TTCP can be used as the basic calcium phosphate to form stoichiometric hydroxyapatite cement formulations, whereas α(alpha)-TCP is used as the basic calcium phosphate for calcium-deficient hydroxyapatite (CDHA) to obtain a more rapidly resorbed material. Furthermore, setting times can be shortening by using liquid accelerators, such as phosphoric acid, acetic acid, lactic acid, citric acid, and acrylic acid. These liquid accelerators temporarily drop the pH of the cement to increase the solubility of the reactants and the rate at which the soluble ions reach supersaturation with respect to the desired phase. Finally, the chemistry can be adjusted so far to precipitate brushite cement. When the solution pH is greater than 4, hydroxyapatite [HA; $Ca_{10}(PO_4)_6(OH)_2$], calcium-deficient hydroxyapatite (CDHA) or carbonated hydroxyapatite (CHA) cements can be formed. However, when the solution pH is less than 4, brushite cements (dicalcium phosphate dihydrate; DCPD; $CaHPO_4 \cdot 2H_2O$) is formed since HA is soluble at this pH. Under these acidic reaction conditions, calcium phosphates less basic than TTCP and α(alpha)-TCP, such as β(beta)-TCP, can also be used. ChronOs Inject, the only brushite cement used clinically (outside the United States only), is comprised of β(beta)-TCP as the basic calcium phosphate and monocalcium phosphate-monohydrate (MCPM) as the acidic calcium phosphate.This cement has typically been associated with rapid resorption and some inflammation due to its acidic setting condition.

Handling and Setting

Perhaps the most difficult cement system to use for VP and KP are CPCs. Cements need two features to be introduced into vertebral bodies: injectability and cohesion. Unfortunately, these are perhaps the two biggest weaknesses of CPC. Similar to PMMA, CPCs are formed by mixing a powder and a liquid to obtain a paste suitable for injection. Because of the hydrophilicity of the CPCs, they tend to mix with body fluids and lose their cohesion. Though the cohesion of CPCs can be increased by increasing the solid-to-liquid ratio, the resulting increase in viscosity requires a higher injection pressure. Consequently, the paste can dewater during injection, leaving cement solids in the instrumentation. Unlike the liquid monomer of PMMA that becomes part of the cement, the liquid accelerator typically used in CPCs diffuses out of the cement, leaving residual porosity. Consequently, the powder-to-liquid (P/L) ratio is perhaps the most important parameter for CPC cement. This ratio dictates the

strength and injectability of a CPC. At low P/L ratios, the CPC is easily injected but weak and porous.At high P/L ratios, the CPC is more difficult to inject but stronger and denser. Regardless of the P/L ratio, a common drawback is the lack of macroporosity. The result is cement in which fast bone ingrowth does not take place and the cement degrades from outside surface inward [16]. Thus, a balance is needed between the porosity and the mechanical properties of CPCs to obtain cement with good resorption and sufficient strength, as well as good rheological properties.

CPCs set through a slow exothermic reaction resulting in a low temperature rise that is dictated by the rate of dissolution and precipitation. Setting times typically range from 10 to 20 min, and CPCs cure very slowly and reach their maximum strength over a much longer time than PMMA and composite cements. Smaller particle size powders with higher surface areas can be used to increase the rate and facilitate the complete conversion to HA to provide increased strength [33]. However, smaller particle sizes and higher surface areas will require more fluid to form an injectable paste and can ultimately reduce the strength of the cement.

While the slow setting conditions and poor strength are certainly drawbacks, perhaps the biggest drawback is the poor radiopacity of a setting CPC. A setting CPC is difficult to visualize under fluoroscopy and is only clearly visible once it sets. Since the CPCs used in indirect distraction procedures need to be injectable (i.e., low P/L ratio), they will be porous and even more difficult to visualize. Their radiopacity also depends on the porosity of the cement, and in practice they are often not radiopaque enough.

Strength and Biomechanical Properties

Though CPCs are biocompatible and resorbable, they still possess numerous limitations. Apatite cements degrade slowly and can cause inflammation when the cement does not set, primarily from the liquid accelerators and acidic calcium phosphates [34]. Brushite cements are more degradable than apatite cements but resorb too quickly in vivo and suffer a rapid decrease in strength (although the mechanical properties of the healing bone increase as bone ingrowth occurs) [35, 36]. Finally, they do not set reliably and are very difficult to inject. The tensile strength for CPCs, for practical purposes, is nonexistent, and compressive strengths are low. More importantly, the fatigue life under physiological loads is very limited [37]. As a result of these poor mechanical properties, CPCs depend upon bony ingrowth to maintain their physical properties. Animal studies have shown that the mechanical properties of apatite CPCs tend to increase continually, in contrast to those of brushite CPCs, which initially decrease because of their rapid resorption characteristics and then increase when bony ingrowth occurs [16]. However, improving the mechanical properties of CPCs is an extensive area of research and has focused on incorporating polymeric additives as a solution or as fibers.

Despite the great difference in mechanical properties between PMMA and CPCs, biomechanical studies of indirect distraction procedures suggest that the mechanical properties of CPCs are adequate. Numerous researchers have demonstrated that CPCs and PMMA perform comparably in simple stress tests but noted that differences in performance did exist. Lim et al. performed biomechanical testing of CPCs and PMMA in a vertebroplasty model and compared control vertebrae versus vertebrae infiltrated with CPCs or PMMA. In their tests, CPCs and PMMA performed similarly [38]. Tomita et al.'s results were similar to Lim's in that the strength and stiffness of vertebrae injected with CPCs and PMMA were similar whether or not the indirect distraction procedure was VP or KP [39]. Belkoff et al. compared the biomechanical properties of Cranioplastic^{TM} (PMMA) and BoneSource^{TM} (CPC) in an ex vivo cadaver spine model. Unlike the previous reports, PMMA resulted in stronger repairs in the thoracic region, but the results were similar in the lumbar regions when compared to the CPC. Belkoff et al. concluded that both materials restored or increased the vertebral strength but not the stiffness [40, 41]. Tomita et al. also confirmed that CPCs could restore strength but not stiffness [42]. Bai et al., in their biomechanical studies, compared the compressive strength, stiffness, and height restoration of intact osteoporotic vertebrae and fractured osteoporotic vertebrae using PMMA and CPCs. Intact osteoporotic vertebrae possessed a fracture strength of 527 ± 43 N and a stiffness of 84 ± 11 N/mm. When infiltrated with PMMA and CPCs, the strength and stiffness increased to 1036 ± 100 N (156 ± 8 N/mm stiffness) and 1063 ± 127 N (157 ± 21 N/mm stiffness), respectively. When treating fractured vertebrae, both PMMA and CPCs restored strength and resulted in an anterior vertebral height increase of 58%. Bai et al. concluded that there was no difference between PMMA and CPCs [43]. Perry et al. also reported similar results with calcium sulfate when compared with PMMA [44].

Whereas the static testing described in the previous paragraph suggests that PMMA and CPCs perform comparably, fatigue testing reveals differences in mechanical behavior. Wilke et al. developed a method for simulating in vivo dynamic loading in vertebral compression fractures to compare the effect of kyphoplasty and vertebroplasty, as well as different augmentation materials. Their results

demonstrate that subsidence in kyphoplasty was greater than in vertebroplasty, regardless of augmentation materials. However, after 100,000 cycles of eccentric loading, small fatigue cracks were observed for CPCs, whereas PMMA showed no signs of fatigue [45]. These results highlight the underlying concerns regarding the use of CPCs in VP or KP. Given the low strength and fracture toughness of CPCs, how do CPCs behave under fatigue loading in KP or VP? If CPCs do break down after prolonged fatigue loading, does bony ingrowth occur to support the structure, and what is the functional clinical outcome?

Calcium Phosphate Cement Resorption and Remodeling

Properties such as composition, pore size, pore volume, and crystallinity dictate the extent to which calcium phosphate cement will be remodelable or resorbable. For example, a brushite CPC is more resorbable than an apatite CPC due to differences in composition and their subsequent solubility. In addition, Norian® SRS (Synthes) and α(alpha)-BSM® (Etex-Merck) are therefore expected to resorb faster than BoneSource® (Orthofix-Howmedica), Biopex® (Mitsubishi), and Cementek® (Teknimed) due to their nonstoichiometry and poorer crystallinity (Table 20.2).Young et al. reported a 30% decrease in the volume of Norian® SRS in a rabbit femur after 24 months [46]. In this study, Norian® SRS was resorbed via normal cellular remodeling and maintained strength during remodeling. Calcium sulfates such as MIIG® X3 (Wright Medical Technology) are options if faster resorption is needed, but the major concern is that it could resorb before the bone grows into the defect, although this does allow for macroporosity, which could accelerate the resorption [47].

Resorption could be a drawback if it occurred too early, before new bone formation, in osteoporotic bone. Furthermore, chronic micromotion could prevent bony ingrowth as the CPC resorbs.In an unstable sheep tibial defect model, CPCs were subjected to fatigue loading. By 20 weeks, significant fibrous tissue was present in the defect site, preventing bony growth [48]. While tangential to a KP or VP model, this study does suggest exercising some caution when utilizing CPCs in load-bearing environments.

Clinical Findings

Unlike PMMA, CPCs do not have the risk of nerve injury resulting from exothermic reactions and hypotension due to monomer release into the vascular system and can promote bony ingrowth.They do suffer from similar complications associated with the use of viscous liquids in indirect distractions, i.e., leakage and subsequent embolism. Based on recent studies and additional FDA scrutiny, CPCs may pose a higher risk for embolism than originally thought. Nonetheless, the use of CPCs in indirect distraction procedures outside the United Stateshas been positive, whereas the clinical history of CPCs in the United States has been troublesome.

Nakano et al. performed 65 vertebroplasty procedures in 55 patients using Biopex, a chondroitin sodium sulfate containing α(alpha)-TCP-based cement (Mitsubishi Materials). Volumes ranging from less than 2 ml to more than 8 ml were injected. The CPC's P/L ratio varied from less than 2.5 to greater than 3.1. Asymptomatic leakage occurred in 23 cases, similar to results seen with PMMA (37.5%). The authors concluded that the risk factors for CPC leakage were similar to those for PMMA [49].

Hillmeier et al. compared Calcibon (Biomet Europe), an α(alpha)-TCP-based CPC, to PMMA using KP. Ninety-nine patients (173 vertebral fractures) were treated with PMMA, and 66 cases (127 vertebral fractures) with Calcibon. Both cements possessed similar clinical outcome via KP with no reported fatalities [50]. Maestretti et al. also clinically evaluated Calcibon using KP. No major complications were observed, similar to Hillmeier et al.'s results. Furthermore, Maestretti et al. monitored the resorption of Calcibon and observed that 20.3% (0.3–35.3% range) resorption of Calcibon was observed at one year. However, the broad range in resorption highlights the unpredictability of CPCs since this process is related to the individual's biological metabolism [51]. In further studies with Calcibon, Libicher et al. reported that KP with Calcibon clinically resulted in total coverage with bone relative to only 30% coverage with PMMA.Images also demonstrated resorption and bony ingrowth into the CPC [52]. In another study, Libicher et al. evaluated the volume of intravertebral cement after balloon kyphoplasty with high-resolution computed tomography of a Calcibon compared to PMMA. After 12 months, the mean volume reduction of Calcibon was 0.08 ml, which corresponded to a resorption of 2 percent vol [52]. These results are somewhat contradictory to Nakano's results and again illustrate the variability in the product and the unpredictable biology.

While CPCs are more biocompatible, osteoconductive, and resorbable than PMMA, the use of CPCs in KP or VP possesses its own unique set of risks.For example, the use of Norian in VP has been associated with patient death [53]. While the mechanism is not clear, Bernards et al. have suggested that Norian stimulated clot formation, resulting in a fatal pulmonary embolism [54]. They reported a mortality rate of up to 86% after the

intravenous injection of 2 ml of Norian in pigs, with mortality increasing as the elapsed time from mixing to injection increased. Cardiovascular changes included an increase in pulmonary arterial pressure and CO_2 tension and a decrease in arterial blood pressure and hypoxia. Krebs et al. performed a similar study in ewes, comparing PMMA to an experimental α(alpha)-TCP-based cement [55]. However, no thromboembolism and fatalities were observed, but an increase in pulmonary arterial pressure and a decrease in arterial blood pressure occurred, similar to the results seen with Bernards et al.'s work [54] but insufficient to cause pulmonary embolism. The major difference between the two studies was the cement formulation. In the Bernard et al. study, Norian was utilized, whereas Kreb et al. utilized a sodium hyaluronate containing experimental α(alpha)-TCP-based cement, illustrating that differences in CPC chemistry can result markedly different outcomes. According to Krebs et al., their cement improved cohesion relative to Norian, which could have prevented pulmonary embolism [55].

Future Technologies for Use in Indirect Distraction

Future technologies for use in indirect distraction will likely involve a combination of advances in instrumentation design, materials, and orthobiologicals. One of the primary concerns regarding indirect distraction procedures is related to extravasation and the related risk of pulmonary embolism. StaXX® FX (Spinewave), approved for use in structural kyphoplasty, is one potential approach to reducing extravasation. With the StaXX® FX instrumentation, 1-mm-thick plates of PEEK are inserted into the vertebral body to restore kyphosis via a lateral or posterior lateral approach and are cemented together with a small amount of PMMA. However, StaXX® FX requires the use of 8-mm-wide PEEK wafers and instrumentation considerably wider. While the extravasation risk is minimized, this procedure is considerably more invasive than VP and KP. In development are certain to be other geometries of solid objects via traditional pedicular and nontraditional extrapedicular approaches to restore kyphosis that allow for a minimally invasive procedure while minimizing extravasation. Furthermore, these solid objects could be PEEK, titanium alloys, structural calcium phosphates, resorbable polymers, or composite. Other approaches to prevent extravasation include utilizing a variety of meshes to restrict cement flow.

Another approach to preventing extravasation is utilizing the free radical polymerization used in PMMA to develop a new class of cement for use in the indirect distraction procedure, such as Cortoss® (Orthovita). Though widely used in dental applications, composite cements such as Cortoss® have not been widely used in orthopedics. Composite cements typically comprise a free radical polymerizable monomer and a specifically engineered glass filler. These engineered glass fillers have been designed so that they can be compounded with the monomers to a high volume percent (as high as 70 wt%) and still maintain a sufficiently low viscosity to be injected. Furthermore, the surfaces of these glass fillers are treated with coupling agents so that they will form a chemical bond with the monomer. When fully cured, these composite cements are extremely strong, biocompatible, and abrasion-resistant.

Cortoss® combines biocompatibility and easy handling, using a "mix-on-demand" system.It is a low-viscosity cement with mechanical properties superior to PMMA and CPCs. The salient properties of Cortoss are that its monomers are nonvolatile, the viscosity remains constant until it sets, it has a maximum exotherm temperature of 63°C, it has an elastic modulus close to cortical bone, and it has surface bone bonding [56]. The resin components include bisphenol-A-glycidyl dimethacrylate (Bis-GMA), bisphenol-A-ethoxy mimethacrylate (Bis-EMA), and triethylene glycol dimethacrylate (TEGMA). Unlike PMMA, which polymerizes into a linear thermoplastic, Cortoss polymerizes into a highly cross-linked thermoset, resulting in a shorter setting time than PMMA [16]. The resins have been used extensively in dental and orthopedic applications and were developed in order to offset such disadvantages of PMMA such as its exothermic reaction and release of unreacted monomer. Fillers used in Cortoss are a glass ceramic to promote bone bonding, barium boroaluminosilicate glass for radiopacity and strength, and thixotropic silica to reduce viscosity.

Unlike the laborious mixing methods needed for PMMA, Cortoss's "mix-on-demand" system provides for perhaps one of the simplest preparation techniques. Cortoss is a two-part system that is aseptically packaged in a conventional epoxy cartridge. Using a gun, the components are forced through a mixing tip at the time of injection. The disposable mixing tips blend the two pastes automatically at the time of injection, initiating the setting reactions. While this "mix-on-demand" delivery system theoretically allows direct injection of the cement, physicians may still prefer traditional cannula delivery systems, as they provide superior tactile feedback and reduce the risk of cement leakage.However, the system of syringes and catheters for the injection of the cement is not ideal. The snap set could also be dangerous and could lead to a blockage of the needle inside the vertebral body, as no feedback is provided to the surgeon as to when Cortoss will set. The set time is 3.5–8.0 min. We believe that an

optimized product will include a modified delivery system designed for greater safety.

In comparison to PMMA, Cortoss possesses an impressive array of mechanical properties: a compressive strength of 210 MPa, a tensile strength of 57 MPa, and a compressive fatigue strength of 120 MPa at 1 million cycles. Another benefit Cortoss relative to PMMA is its superior biocompatibility. A study comparing the biocompatibility and interfacial bond strengths of Cortoss versus PMMA (Simplex® P) implanted into rabbit femurs for up to 52 weeks and in sheep long bones for up to 78 weeks showed new periosteal and endosteal bone were formed within defect sites filled with either of the cements. However, the initial response was greater with Cortoss than with the PMMA. Unlike PMMA, new blood vessels invaded the periphery of Cortoss implants. Both cements were surrounded by bone in the long term, but at 24 weeks, half the Simplex P specimens were separated from bone by a layer of fibrous connective tissue. In terms of displacement forces, this study also showed an augmentation with time for both cements, but these displacement forces were greater for a rod held in place with Cortoss than with PMMA. A relative strength difference of 4.5 N was observed between the two cements after 24 weeks and could be attributed to a faster initial bone response and a greater degree of mineralization around Cortoss. The initial clinical findings for using Cortoss in indirect distraction show that pain relief was similar to PMMA.

While these approaches and materials can adequately address the needs of the patient suffering osteoporotic vertebral compression fractures, more advanced cement technologies and orthobiologicals will be required to treat younger patients suffering from vertebral fractures. In these cases, injecting Cortoss or inserting slivers of PEEK may be undesirable, whereas an injectable, load-bearing, resorbable cement may be more desirable. Though numerous companies are developing such cements, none has yet to reach the market. The previous experience with CPCs suggest that these load-bearing, resorbable cements are likely not be a pure phase calcium phosphate but a composite between calcium phosphate or calcium salts, similar to Orthovita's Cortoss but utilizing a resorbable resin chemistry. Such chemistries are not likely to utilize free radical polymerization, but instead will use addition chemistries.In the case of insertion of solid devices, materials are limited to structural calcium phosphates, resorbable polymer, or composites thereof. Furthermore, the desire for more rapid bony ingrowth and replacement will likely require the use of orthobiologicals such as growth factors (i.e., bone morphogenic proteins, platelet-derived growth factors, vascular endothelial growth factors, etc.) or stem cells. While it is easier to visualize the use of orthobiologicals with solid implants, where a solution or gel containing the growth factor or stem cell is injected into the interstices between the solid implants, combining orthobiologicals with cements is likely to be more challenging. Since these orthobiologicals are sensitive, the cement formulation should be very mild in terms of setting reaction. Nonetheless, we believe that we have revealed only the tip of the iceberg in terms of innovations related to indirect distraction procedures and that the next few years should be exciting for practitioners.

Conclusion

Though the functional outcomes for indirect distraction procedures have been positive, many improvements can be made to materials and instrumentation that will reduce risks to the patients and allow for a broader cross section of patients. Current cement formulations still require mixing a solid and a liquid and subsequent manipulation into an injection device. Furthermore, once the cement has been mixed, the surgeon has a limited time to use the cement. In future formulations, easier preparation and handling would be desirable, and we believe that mix-on-demand methods would largely address these issues. Mix-on-demand methods would also provide for longer working times and allow for injection immediately after preparation, unlike PMMA. Also, whether cements or solid structural devices are utilized, all methods should be easily inserted via a minimally invasive approach. In the case of cements, the setting reactions should occur at body temperature and be biocompatible. In addition, both cements and structural devices need to be osteoconductive, possess a microstructure to facilitate bony ingrowth, and have a range of resorbability.

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NOTE: The letters "*f*" and "*t*" followed by locators refer to figures and tables respectively.

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