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Minimally Invasive Spine Surgery

Surgical Techniques and Disease Management

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Preface

Despite the rapid evolution of minimally invasive spine (MIS) surgery over the past decade, there exists little consensus among spine surgeons regarding the precise definition of this field. Is minimally invasive spinal surgery defined by the length of the incision, the minimizing of damage to collateral structures, expedited recovery, or reduced surgical risks and complications? In reality, all of these are worthwhile goals that surgeons should strive to accomplish without sacrificing the ultimate aims of the procedure. Many quality studies have indeed shown reduced perioperative morbidity, blood loss, surgical time, and length of hospital stay, while at the same time showing economic value to a number of established MIS procedures. In today's health-care environment, assessing the value of surgical procedures has become a critical metric increasingly relied on by surgeons, payers, policy makers, and patients for informed decision-making.

Although advanced enabling technologies have resulted in minimally invasive spine surgery becoming more reliable, reproducible, and safe, there remains a difficult learning curve. Being facile with open surgical procedures does not necessarily translate into minimally invasive skills. It is important to realize that MIS surgery need not be an all-or-none phenomenon and is rather a progressive journey of acquiring knowledge and skills. In *Minimally Invasive Spine Surgery*: *Surgical Techniques and Disease Management*, we have attempted to address many of these challenges. In addition to highlighting surgical techniques and procedures, we have also focused on decision-making and application of the varied MIS techniques to address common and rare spinal conditions. We have assembled experts and thought leaders in the field to critically appraise various techniques of MIS surgery. We have encouraged discussion of the evidence base for the recommended procedures.

Our goal with this book is to provide a comprehensive text covering more established as well as innovative techniques of MIS surgery. This has only been possible because of the collective expertise and wisdom of the outstanding contributors to this book, many of whom have played significant roles in the development and advancement of the field. We hope this book will serve as a resource for trainees as well as experienced spine surgeons.

Chicago, IL — Frank M. Phillips
Plano, TX — Isador H. Lieberman
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I would like to express my deep gratitude to Denise, Gina, and Jay, who have supported, inspired, and loved me along this journey.

I dedicate this book to the many talented young spine surgeons that I have had the honor of educating. Your insights, enthusiasm, and search for the "truth" have kept it real and motivate us all to search for answers that will improve outcomes for our patients.

Frank M. Phillips

To Deeci, Rachelle, Josh, and Danielle, who continue to support and inspire me day after day.

Isador H. Lieberman

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Part I

Introduction

History and Evolution of Minimally Invasive Spine Surgery

1

Omar N. Syed and Kevin T. Foley

Introduction

The development of minimal access approaches to the spine has revolutionized the arsenal of the contemporary spine surgeon. Traditional open approaches to the spine, although familiar to spine surgeons, are associated with approach-related morbidity. The tissue injury that occurs during the surgical approach can result in increased blood loss, increased postoperative pain, lengthened recovery time, and impaired spinal function. Thus, less invasive techniques that can achieve the same goals as traditional approaches while minimizing the approach-related morbidity are desirable [1].

Advances in surgical technique and technology have enabled the "reinvention" of several commonly performed spinal procedures through the adoption of minimally invasive approaches. Such advances in microscopy, tissue retractors, and specialized instruments have allowed surgeons to perform procedures through smaller incisions [2].

Minimally Invasive Spine Surgery

Benefits

The use of small surgical corridors to approach pathology is seen in various surgical subspecialties. One such example is the use of laparoscopic cholecystectomy as the primary operative treatment for symptomatic gall bladder disease. This approach has been associated with less surgical-related morbidity, better long-term postoperative outcomes, and decreased costs largely due to shorter postoperative hospital stays [3, 4]. In orthopedics, arthroscopy of joints such as the knee, shoulder, and hip has significantly reduced the approach-related morbidity and improved outcomes [1].

With respect to lumbar spinal surgery, morbidity is related to the significant iatrogenic muscle and soft tissue injury that occurs during routine exposure. Biochemical reaction and morphological alteration have clinically significant implications with reduction in muscle strength, decreased endurance, and increased pain [5]. Kawaguchi and colleagues proposed that muscle injury is due to a crush mechanism related to the use of forceful self-retaining retractors [6, 7]. Elevated serum levels of creatine phosphokinase MM isoenzyme, a marker of muscle injury, are directly related to the retraction pressure and duration. In fact, studies show increased levels of several circulating markers of tissue injury including aldolase, interleukin-6 and interleukin-8, and glycerol [2]. Stevens et al. [8] and Tsutsumimoto et al. [9] studied MRIs in patients with traditional open approaches to the lumbar spine and compared them with patients undergoing mini-open approaches. These studies showed decreased intramuscular edema and decreased atrophy in the mini-open approach patients. Styf and Willen determined that retractor blades increase intramuscular pressure to levels of ischemia [10]. Rantanen et al. concluded that patients with poor outcomes after lumbar spine surgery are more likely to have persistent selective type-2 muscle fiber atrophy and pathological structural changes in the paraspinous muscles [11]. Sihvonen has demonstrated that local denervation atrophy due to damage of dorsal rami after lumbar spine surgery is associated with an increased risk of failed back syndrome [12].

Another key concept of minimally invasive spine surgery is to limit the amount of tissue resection to minimize postoperative spinal instability, specifically by limiting the disruption of the facet joint and the midline interspinous ligament-tendon complex [2]. A finite element analysis showed that minimizing bone and ligament removal resulted in greater preservation of normal motion of the lumbar spine after surgery [13].

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Limitations

As with any new surgical technique, a learning curve is necessary to become proficient in minimally invasive surgery. Spine surgeons are familiar and comfortable with the anatomy when it can be directly visualized. However, minimally invasive exposures are generally limited to the area of surgical interest and certain key anatomic landmarks within this limited field of view. Familiarity with the anatomy allows the surgeon to safely perform the surgery without exposing structures that are not being treated surgically. Minimally invasive spine techniques are also more technically demanding, as surgeons must be facile when working through small channels and longer distances, often employing the use of bayoneted instruments. McLoughlin and Fourney analyzed the depth of the learning curve involved in minimally invasive lumbar microdiscectomies and found that it took about 15 cases for spine surgeons to become comfortable with, and proficient at, the technique. Operative times and complications for minimally invasive microdiscectomy were reduced as the surgeon became more experienced with the technique [14, 15]. Additionally, while loupe magnification and endoscopy can be used, the use of the operative microscope can greatly enhance illumination and visualization. Recent developments have allowed stereoscopic high-definition visualization of the field of view in real-time on three-dimensional (3D) flat panel displays in the operating room. This technology is also useful for recording 3D surgical video for educational purposes and presenting on-demand and streaming 3D surgical video content. The technology has significant implications for surgeon education.

Minimally invasive techniques will oftentimes require the use of intraoperative fluoroscopy or image guidance. The surgeon needs to master the use of these systems in order to complete the surgery in a safe, effective manner. For example, the interpretation of fluoroscopic images can be challenging for surgeons who have not had significant experience using two-dimensional images to determine their three-dimensional surgical position.

Finally, while minimally invasive spinal techniques have been used for the past decade, only now are long-term results being reported [16, 17]. More studies are necessary to validate many of these techniques.

Minimally Invasive Surgery in the Lumbar Spine

Percutaneous Techniques

The first report of a percutaneous approach to the lumbar spine is generally credited to Pool. In 1938, he described the use of a modified, battery-operated cystoscope to visualize the cauda equina, a technique he termed "myeloscopy" [18]. The technique was employed for diagnostic purposes.

Smith reported the use of chemonucleolysis for the treatment of symptomatic herniated nucleus pulposus in humans by percutaneous injection in 1964 [19]. Chymopapain was discovered and isolated in 1941 by Jansen and Balls from the latex of the fruit of *Carica papaya* [20]. Chymopapain is a proteolytic enzyme that can reduce the water content of the nucleus pulposus and cause reduction in disc height and bulge [21]. Despite approval by the Federal Food and Drug Administration in 1982, surgeon interest in this modality has diminished, as the efficacy of this technique for disc pathology remains speculative. As well, it has been associated with anaphylaxis, epidural scarring, and transverse myelitis [22].

The first percutaneous nucleotomy was performed by Hijikata in 1975. He employed a posterolateral approach using a 2.6 mm diameter cannula to fenestrate the annulus and partially resect the nuclear substance. The procedure reportedly reduced intradiscal pressure and obtained relief of irritation of the nerve root or the pain receptors around the disc [23]. In 1983, Kambin and Gellman performed a discectomy through a posterolateral approach using a Craig cannula and small forceps after an open laminectomy [24]. In 1986, Schreiber described "discoscopy," in which he added an arthroscope to percutaneous nucleotomy for direct visualization [25].

A similar percutaneous technique employing an endoscope was subsequently described by Mayer and Brock in 1993 [26]. Faubert and Caspar also described their technique of percutaneous discectomy using a 5.4 mm diameter cannula (with a 4.6 mm internal diameter) and a fluoroscope, but with no direct visualization [27]. Various automated disc removal instruments were added to the approach as described by Onik and Maroon [28, 29]. They described a percutaneous nucleotomy procedure which employed a blunt-tipped, suction-cutting probe (nucleotome) in a procedure termed automated percutaneous lumbar discectomy (APLD). Principles of its mechanism involved rhythmic irrigation, aspiration, and cutting to retrieve disc material from inside the annulus [30]. Around this time in the early 1980s, the idea of using a laser in the treatment of lumbar disc herniations arose. Ascher and Heppner, in 1984, were the first to use lasers to treat lumbar disc disease [31]. Theoretically, the application of laser energy, as delivered percutaneously through a cannula, would evaporate water in the nucleus pulposus resulting in a reduction of intradiscal pressure. This was postulated to cause the herniated disc material to recede towards the center of the disc, thus leading to reduction of nerve root compression and relief of radicular pain [32, 33]. After a series of in vitro experiments, Choy and colleagues performed the first percutaneous laser discectomy on a human patient in 1986 [34, 35]. In the 1990s, Saal and Saal introduced intradiscal electrical thermocoagulation (IDET). This technique also employs a percutaneous approach, similar to nucleotomy or APLD; however, heat is applied using a thermoresistive coil [36]. It is specifically designed to treat pain from internal disc disruption and annular tears.

Historically, the indications for percutaneous discectomy have generally been limited to contained lumbar disc herniations. Lumbar radiculopathy secondary to large, free fragment (noncontained) disc pathology, migrated disc fragments, and bony compression of the nerve root have been contraindicated to percutaneous lumbar discectomy [37]. The efficacy of percutaneous nucleotomy and laser discectomy has been questioned. In a recently updated Cochrane review, Gibson and Waddell concluded, "At present, unless or until better scientific evidence is available, automated percutaneous discectomy, coblation therapy, and laser discectomy should be regarded as research techniques" [38]. However, despite the facts that conclusive evidence is lacking, randomized multicenter trials do not exist, and many of these procedures are labeled as experimental [33, 38], intradiscal therapies and percutaneous mechanical disc decompression techniques continue to increase [33, 39].

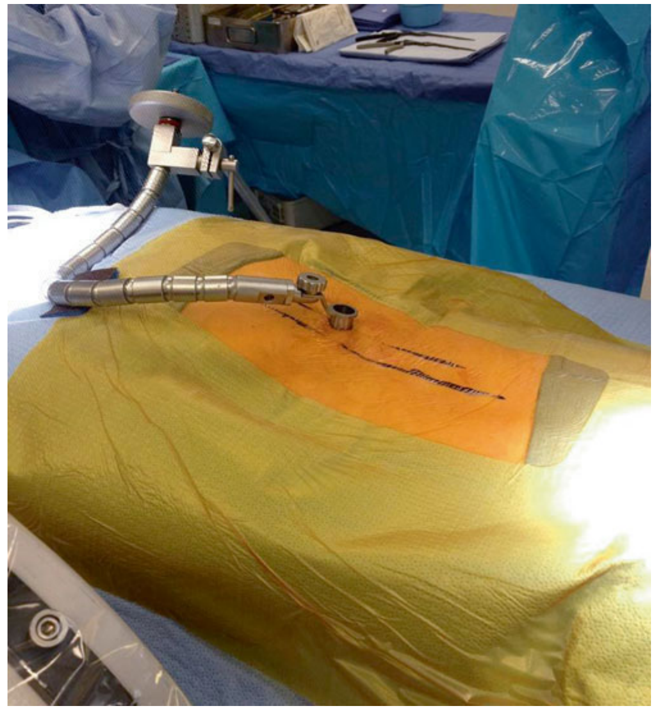

Fig. 1.1 A 16 mm diameter tubular retractor has been inserted for performance of a lumbar microdiscectomy

Lumbar Decompression Using Tubular Retraction

The use of a tubular retractor system for lumbar surgery was described by Foley and Smith in 1997 [37]. The microendoscopic discectomy (MED) system was specifically designed by the senior author (K.T.F.) to address the limitations of percutaneous nucleotomy and percutaneous endoscopic transforaminal approaches. Concerns regarding prior minimally invasive approaches to discectomy included the inability to adequately visualize the relevant anatomy and pathology and ergonomic issues related to small cannulae and tiny instruments. Lastly, in the senior author's personal experience with nucleotomy, failure to adequately decompress the nerve roots resulted in reoperation in several patients. Therefore a tubular retractor system was specifically designed to address these issues while remaining a minimally invasive procedure that utilized a muscle-sparing, percutaneous approach. The system consists of a series of concentric dilators and thin-walled retraction tubes of varying lengths. The spine is accessed via serial dilation of the natural plane between muscle fascicles, instead of a traditional muscle-stripping approach. The use of a tubular retractor, rather than blades, allows the retractor itself to be thin-walled (0.9 mm) and circumferentially defines a surgical corridor through the paraspinous muscles. The tube is held in place by an articulated, repositionable arm that also connects to the operating table. Unlike expanding bladed retractors, which rely on muscle tension to stay in position, tubular retractors minimize and evenly distribute the pressure on the surrounding paraspinous tissues. All of the midline supporting musculoligamentous spinal structures are left intact with this technique. An appropriately sized working channel is created that permits spinal decompression and fusion. Surgery can be performed using the operating microscope, loupes, an endoscope, or a combination of techniques, depending on the preference of the surgeon [5, 40]. The system has been used to provide minimally invasive access for a broad range of cervical, thoracic, and lumbar pathologies. Figure 1.1 illustrates a 16 mm diameter tubular retractor in place during microdiscectomy. Figure 1.2 shows the healed skin incision after completion of the microdiscectomy.

Fig. 1.2 A small, healed incision is visible following a lumbar tubular microdiscectomy

The tubular retractor system for microdiscectomy of herniated discs is the most common minimally invasive spine surgery performed in the United States [2]. However, limitations with the initial MED system included the fact that the endoscope was not reusable, image quality was inconsistent, and the working space within the tubular retractor was limited [41]. The lack of depth perception and stereoscopic visualization associated with the use of the endoscope prolonged the learning curve of the procedure [21]. To address these limitations and as surgical applications for this technology expanded, the MED system evolved into a more versatile tubular retractor system. Compared with the initial system, the modified system has additional advantages, including improved image quality, three-dimensional visualization, decreased endoscopic diameter, variable tubular retractor size, increased available working room within the tubular retractor, and decreased per case cost [41]. Unlike prior percutaneous approaches, the use of tubular retractors allows surgeons to address not only contained lumbar disc herniations but also sequestered or migrated disc fragments and lateral recess stenosis [41].

Data from six prospective randomized controlled trials comparing minimally invasive discectomy with tubular retractors to open discectomy (with a total of 837 patients) were pooled in a recent meta-analysis by Dasenbrock [42–48]. Incidental durotomies were reported significantly more frequently during minimally invasive discectomy, which may be due to the learning curve associated with this procedure. However, the total incidence of complications did not differ between the open and minimally invasive approaches. The current evidence suggests that both open and minimally invasive tubular retractor discectomy lead to a substantial and equivalent degree of short-term and long-term improvement in leg pain, the primary symptom of most patients with lumbar radiculopathy [42].

Tubular retractor systems have been used to address spinal pathology other than herniated discs. Guiot and colleagues, Khoo, and Palmer described a technique of bilateral decompression via a unilateral tubular approach for lumbar spinal stenosis [49–51]. After a standard unilateral decompression is performed, the working channel of the tubular retractor is angled medially, allowing for a central and contralateral decompression. The dural tube can be gently retracted, and the ligamentum flavum and the medial portion of the contralateral articular processes can be resected to achieve a bilateral decompression using a drill, Kerrison punches, and curettes [49, 50, 52]. The Tubular retractor systems have also been applied to address far lateral disc herniation [53], recurrent disc herniation [54], synovial cysts [55, 56], tethered cord syndrome [57], and intradural tumors [58, 59] among other applications [60].

Minimally Invasive Fusion and Fixation Techniques: Posterior

Efforts to minimize the approach-related morbidity of lumbar fusion can be traced to Watkins. In 1953, he reported a paraspinal approach between the planes of the sacrospinalis and the quadratus lumborum to expose the transverse processes for posterolateral lumbar fusion [61]. Subsequently, Wiltse described a modified transmuscular approach for spondylolisthesis using a longitudinal separation of the sacrospinalis group between the multifidus and longissimus [62].

Effective lumbar fusion, both open and minimally invasive, has generally relied upon effective means of internal fixation. Thus, the development of techniques for minimally invasive lumbar fusion has paralleled the development of techniques for minimally invasive lumbar fixation. Current options for percutaneous lumbar fixation include facet screws and pedicle screws. Facet screws fix the spine in situ and should be used only when the posterior spinal elements are intact (e.g., following an ALIF). Percutaneous pedicle screws, on the other hand, can be used following a posterior decompression or when the posterior elements are deficient (e.g., lytic spondylolisthesis). As well, pedicle screws can be used to apply corrective forces to the spine and to compress interbody grafts. For these reasons, we prefer pedicle screws for minimally invasive lumbar fixation.

Magerl described the use of percutaneous lumbar pedicle screws with long shafts (Schantz screws) and an external fixator in 1982. Initially, his system was used for external skeletal fixation of the lower thoracic and lumbar spine in spinal fracture cases [63]. The limitations of this technology included the risk of infection, patient discomfort associated with the external instrumentation, and the need to remove the instrumentation at a later date. However, it allowed for the evolution of techniques for minimally invasive lumbar fusion. Using Magerl's external fixator, Leu described a staged procedure for single-level percutaneous lumbar fusion in 1993 [64]. The technique did not allow for bony decompression and was limited to single segments. In a first procedure under general anesthesia, a Magerl external pedicular fixator was applied to the patient. In a second procedure at a later date, bilateral 7 mm diameter cannulae were inserted via a posterolateral, percutaneous approach 9–11 cm off the midline. The cannulae were passed through the annulus into the interbody space, where a nucleotomy was performed and the end plates were abraded with special instruments. Iliac bone graft that had been harvested through a separate incision was then inserted into the disc space through the cannulae. Finally, in a third procedure approximately 3 months later, the external fixator was removed. Leu reported 33 patients who had been operated upon using this technique from October 1988 to January 1991. The reported fusion rate for these cases was 84 %.

Mathews first described and performed a wholly percutaneous lumbar pedicle fixation technique in which he used plates as the longitudinal connectors in 1995 [65]. In his procedure, pedicle screws with long, smooth shafts above the threaded portions (similar to Magerl) were employed, but the screw shafts were connected with subcutaneous plates that were passed between the two screw incisions, applied to the screw shafts under direct vision, and then secured under direct vision utilizing nuts. In 2000, Lowery described a similar technique in which subcutaneous rods were used to connect the long screw shafts rather than plates [66]. With both the Mathews and Lowery procedures, the longitudinal connectors were placed superficially, just beneath the skin [65, 66]. This had several potential disadvantages. First, the superficial hardware could be irritating and required routine removal [66]. Second, longer screws (and thus longer moment arms) were required, producing a less effective biomechanical stabilization than that achieved using standard pedicle fixation systems and leading to a higher potential for implant failure.

In 2001, Foley and colleagues described a system for percutaneous pedicle screw/rod insertion to address the limitations of the prior techniques for percutaneous thoracolumbar fixation [67, 68]. The design criteria included the ability to percutaneously insert a biomechanically sound pedicle screw and rod construct into a standard, subfascial anatomic position similar to that of traditional open techniques. A key design element was the use of "extenders" that were removably attached to standard-sized pedicle screws. Once the screws had been percutaneously inserted through the pedicles, the extenders allowed the surgeon to align the screw heads remotely for subsequent percutaneous delivery of a rod.

The combination of the tubular retractor and the ability to place standard pedicle screws in a minimally invasive fashion led to rapid advances in minimally invasive fusion. In 2001, Foley published the results from the first cases performed using this system [67, 68]. This included the first tubular posterolateral onlay fusion with percutaneous pedicle screw and subfascial rod placement performed in 2000. The first tubular posterior lumbar interbody fusion (PLIF) with percutaneous pedicle screw and subfascial rod placement was performed by Foley in 2001, presented at the Congress of Neurological Surgeons annual meeting in 2001, and published in 2002 [5]. He reported on the results of tubular PLIF in seven patients. The first tubular transforaminal lumbar interbody fusion (TLIF) with percutaneous pedicle screw fixation was performed in 2001 and reported by Foley, Holly, and Schwender in 2003 [40].

Short-term and midterm outcomes of minimally invasive TLIF have been reported [16, 69]. We recently studied the long-term outcome in patients who underwent minimally invasive transforaminal lumbar interbody fusion for spondylolisthesis or spondylosis with or without radiculopathy with a minimum of 5 years' follow-up [17]. Only those patients who completed a preoperative Oswestry Disability Index questionnaire (ODI) and Visual Analog Score questionnaire (VAS) were included in the study. A total of 37 patients underwent a single-level minimally invasive TLIF. All patients had bilateral pedicle screw fixation and placement of a polyether ether ketone (PEEK) interbody device with autograft and appropriately dosed rh-BMP2. The mean age of the cohort was 63 years (37–80) with a mean follow-up of 72.6 months (60–90 months). Of the 37 patients, 25 had surgery at L4–5 and 12 at L5-S1. All patients had evidence of radiographic fusion at 2 years with none requiring revision surgery. There were 24 patients with low-grade spondylolisthesis (Meyerding Grade I and Grade II), 1 patient with Meyerding Grade III spondylolisthesis, and 12 patients without spondylolisthesis. One out of these 12 suffered multiple recurrent disc herniations at the same level warranting a fusion; the remaining 11 had spondylosis with associated mechanical low back pain and radicular symptoms. Thirty-three patients had a unilateral decompression and four patients had a bilateral decompression. Improvements in average visual analog scale-back pain, visual analog scale-leg pain, and Oswestry Disability Index (preoperative to last follow-up) scores were 50–12, 56–16, and 53–17, respectively. This is the first study with a greater than 60-month follow-up demonstrating long-term durability of minimally invasive TLIF results. The significant improvements in disability, back pain, and leg pain seen in this study suggest that minimally invasive TLIF is capable of producing sustained relief of symptoms and improvement in patient function.

The senior author also described a technique for minimally invasive TLIF that permits the surgeon to reduce spondylolisthesis percutaneously, utilizing translational screw extenders. Figure 1.3 is a schematic showing how reduction is achieved. Figure 1.4 depicts lateral fluoroscopic images showing reduction of a spondylolisthesis using the reduction screw extender [70]. Forty patients who underwent minimally invasive TLIF for symptomatic spondylolisthesis utilizing this approach were studied. Thirty cases involved a degenerative spondylolisthesis while the remaining ten were isthmic. The minimum follow-up was 24 months with a mean of 35 months. The mean preoperative Oswestry Disability Index score was 55 and decreased to a mean of 16 postoperatively. The mean preoperative leg and back pain visual analog scale scores were 65 and 52, respectively, improving to means of 8 and 15, respectively. Reduction of

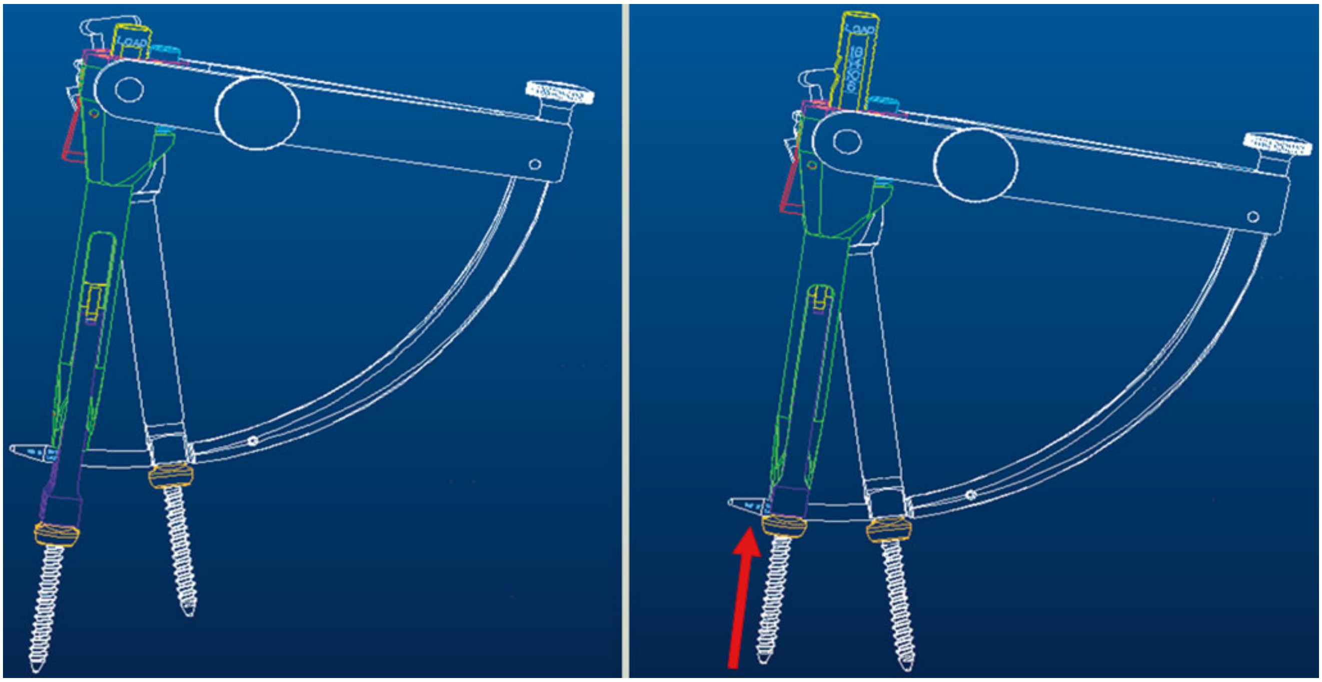

Fig. 1.3 Spondylolisthesis reduction is accomplished by shortening the length of the extender. When the set screw of the standard extender is provisionally tightened, this locks the angle between the rod and the pedicle screw. Turning the drive screw of the reducible extenders shortens its length and pulls the slipped vertebral body towards the rod

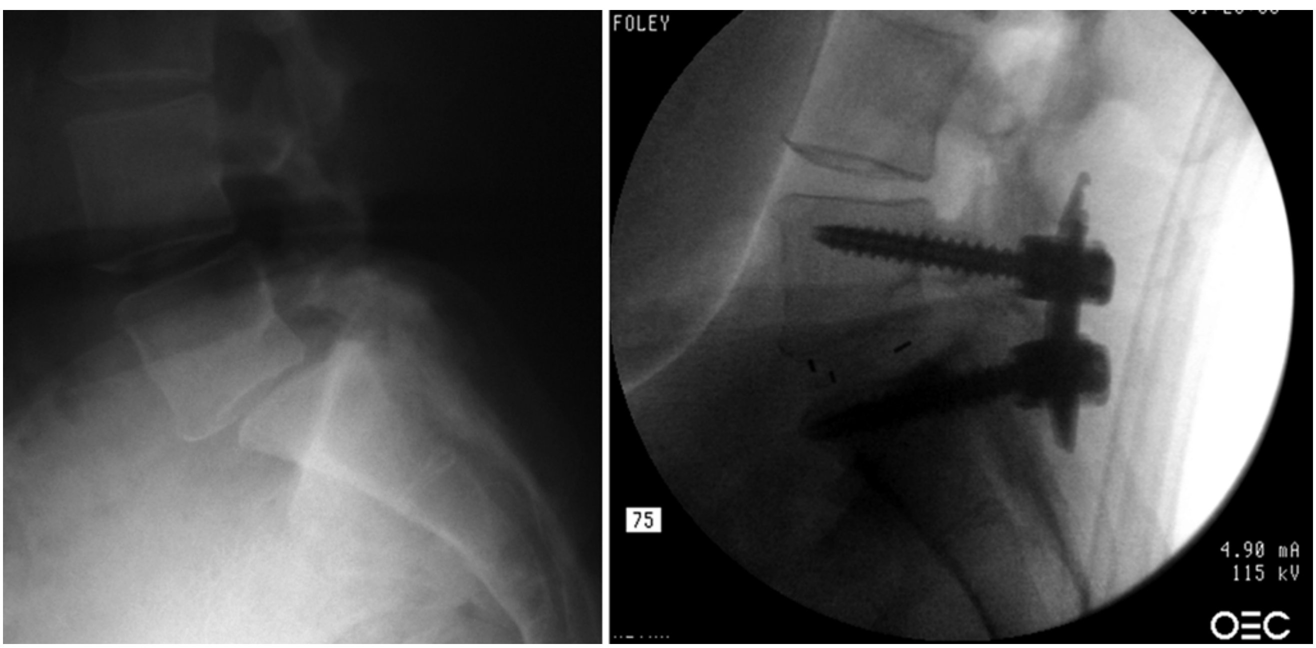

Fig. 1.4 Lateral fluoroscopic images show the spondylolisthesis before and after minimally invasive reduction

the spondylolisthesis was achieved in all cases, with a mean decrease in forward translation of 76 %. The authors conclude that minimally invasive TLIF for symptomatic spondylolisthesis appears to be an effective surgical option with results that compare favorably to open procedures.

During the last decade, the indications for percutaneous pedicle screw fixation and device options for placing them have expanded, permitting surgeons to routinely use percutaneous fixation in multilevel thoracolumbar cases. Currently, percutaneous pedicle screws are used in a variety of spinal disorders, including trauma, spinal neoplasia, infection, revision surgery, and deformity [71].

Recently, a new class of posterior spinal fixation devices called interspinous spacers has been introduced. Theoretically, the insertion of an interspinous spacer provides for indirect decompression by maintaining flexion of a stenotic spinal segment. Ideal candidates for this surgery include patients with neurogenic claudication that is relieved with flexion [72]. These devices can be inserted under local anesthesia in a less invasive fashion than conventional lumbar surgery. The idea dates back to Knowles in 1957; he placed a steel "plug" between the spinous processes to hold the spine in a flexed posture. Unfortunately these devices loosened and were dislodged easily [73]. Currently there are many designs of interspinous spacers. They can be categorized as either static/noncompressible or dynamic/compressible. The first interspinous spacer to be used in the United States for the treatment of patients with neurogenic intermittent claudication due to spinal stenosis was approved by the Food and Drug Administration in 2005. A recent systematic review of the clinical evidence by Kabir concluded that this form of interspinous process spacer may improve outcome when compared to nonoperative treatment in a select group of patients over 50 years old, with lumbar stenosis and neurogenic claudication, who have improvement of their symptoms in flexion. While studies on multiple interspinous devices have shown promising initial clinical results, prospective randomized controlled trials are lacking. Further, good quality trials are needed to clearly outline the indications for their use [72, 74]. A recent report by Epstein raised concerns about high complication rates, reoperation rates, poor outcomes, and high costs for interspinous devices [75].

Minimally Invasive Fusion Techniques: Lateral

The lateral retroperitoneal transpsoas approach is a novel minimally invasive procedure that provides a surgical corridor to the anterior lumbar spine to perform interbody fusion [76]. In 1997, Mayer [77] first reported the technique of a less invasive, retroperitoneal, direct lateral approach to the lumbar spine, which was later refined by McAfee in 1998 to include the use of an endoscope and placement of lateral threaded fusion cages [78]. Subsequently, in 2006, Ozgur, Aryan, Pimenta, et al. described a further evolution of the lateral interbody fusion technique [79]. In this approach, the patient is placed in the lateral decubitus position. Dissection occurs through the retroperitoneal anatomical fat plane, directly down to the psoas muscle. Dilators and a modified tubular retractor are then placed under fluoroscopic guidance to provide access to the appropriate spinal level. To guide dissection through the psoas muscle, intraoperative neuromonitoring is necessary to prevent injury to the lumbosacral plexus. Once the lateral aspect of the disc space has been localized and exposed, discectomy and fusion are performed using standard techniques [30]. An advantage of this approach is that it does not require a second access surgeon. Other advantages are reduced incidence of ileus compared to open anterior approaches, maintained integrity of the anterior and posterior longitudinal ligaments, reduced operative time in comparison to other anterior approaches, and reduced postoperative hospital stay and analgesic requirements [76]. Morbidity for this approach includes transpsoas swelling causing hip flexor weakness, genitofemoral nerve irritation causing numbness or pain of the thigh and groin area, and lumbar plexus injury [80, 81].

Minimally Invasive Fusion Techniques: Anterior

Anterior lumbar interbody fusion (ALIF) has been used for spinal degenerative disorders since 1932, when Carpenter first described the technique for treatment of spondylolisthesis [82]. ALIF was originally performed through an open retroperitoneal approach. In the mid-1980s, reports were published which described a simultaneous combined anterior and posterior approach for spinal fusion [83]. The procedure was characterized by a 25-cm incision extending from the midline to the lateral border of the rectus abdominis, 400–600 cc of intraoperative blood loss, a surgical duration of 3.25 h, and hospitalizations typically lasting 10–14 days [83, 84]. The incorporation of laparoscopy-assisted techniques by gynecologic, urologic, and general surgeons paved the way for these technologies to provide access to the anterior lumbar spine. In 1991, Obenchain reported the first use of a laparoscopic approach to the lumbar spine for a discectomy [85]. In the mid-1990s, mini-open retroperitoneal [77, 86], mini-open transperitoneal [77], laparoscopic transperitoneal [87, 88], and laparoscopic retroperitoneal [78] approaches were developed for ALIF.

A novel method for instrumentation of the lumbosacral spine is through the paracoccygeal transsacral corridor, first reported by Cragg in 2004 [89]. A small paracoccygeal incision is used to develop a corridor in the presacral space. Custom instruments can be directed under fluoroscopic guidance along the midline of the anterior sacrum to the surface of the sacral promontory, where an axial bore can be created through the remaining sacrum into the lower lumbar vertebral bodies and discs. A discectomy can be performed, bone graft can be inserted into the interspace, and an axial threaded screw for fixation can be placed. This procedure is usually accompanied by posterior fixation although it can be performed as a stand-alone under certain circumstances [30]. A recent study by Tobler in 2011 evaluated the 2-year clinical and radiographic outcomes in 156 patients who underwent an L5-S1 interbody fusion and fixation using this approach.

Clinical improvements were realized in back pain severity and functional impairment through 2 years of follow-up, and the overall radiographic fusion rate at 2 years was 94 % (145 of 155) [90].

Minimally Invasive Surgery in the Thoracic Spine

Traditional access to the thoracic spine includes anterior- and posterior-based approaches. Such approaches include posterior transpedicular, costotransversectomy, lateral extracavitary, anterolateral transthoracic, and sternotomy. These techniques, while familiar to the spine surgeon, carry significant morbidity.

One of the first developments applicable to minimally invasive approaches to the thoracic spine was video-assisted thoracoscopic surgery (VATS). A Swedish physician, Hans Christian Jacobaeus, is credited as the pioneer of this technique in 1910 [91]. The development of endoscopic video cameras and improvements in surgical instrumentation further broadened applications of thoracoscopy. The first use of thoracoscopy for the treatment of spinal disease was developed simultaneously by Mack [92] in the United States and Rosenthal [93] in Germany [94]. VATS has been used for infectious processes, including biopsies and drainage, tumor biopsies, thoracic disc herniations, sympathectomies, and anterior releases for deformity correction [95].

The application of tubular retractors to the thoracic spine has been described by Jho and Perez-Cruet [96, 97]. This technique, as for the lumbar spine, involves a series of muscle dilators, a tubular retractor, and an endoscope for visualization, which can reduce much of the morbidity associated with traditional approaches. Recently, lateral approaches to the thoracic spine employing the use of tubular and expandable retractors have been used for tumor removal and traumatic spinal pathologies, including corpectomies and the placement of expandable cages with anterior plating [98, 99].

Minimally invasive thoracic pedicle screw fixation has recently been described. In 2003, Holly and Foley evaluated the accuracy of percutaneous thoracic pedicle screw placement in three cadavers. Fifty-nine of sixty-four screws were placed completely within the pedicles (92 %); the remaining screws violated the pedicle walls by less than 3 mm [100]. In 2006, Ringel and colleagues placed percutaneous posterior pedicle screws in the thoracic and lumbar spine via a transmuscular approach using two-dimensional fluoroscopy alone in 104 patients [101]. The use of cannulated pedicle screws using neuronavigation has also been recently reported by Kakarla [102]. Minimally invasive percutaneous instrumentation has been used for traumatic vertebral body fractures and neoplastic, infectious, and degenerative diseases of the thoracic spine in a safe manner with acceptable rates of accuracy and morbidity [102].

Minimally Invasive Surgery in the Cervical Spine

While there have been tremendous advances in minimally invasive approaches and techniques for the thoracolumbar spine, the same cannot be said for cervical spine surgery. The anterior cervical approach to the spine is a commonly performed procedure and enjoys a relatively low morbidity. Therefore, the impetus to search for alternative cervical options is reduced unless long-segment posterior decompression or stabilization across the occipitocervical and cervicothoracic junctions is necessary [103].

Progress in imaging techniques has allowed for much more thorough preoperative assessment and characterization of the specific indications for posterior cervical approaches. Specifically, with posterolateral cervical nerve root decompression, such as for an intraforaminal disc herniation or cervical foraminal stenosis, a posterior cervical foraminotomy can be effective. The tubular retractors that had success in the lumbar spine were used in the cervical spine. The first application of the microendoscopic discectomy system (MED) for minimally invasive posterior cervical foraminotomy was described by Roh in cadaveric specimens in 2000 [104]. Adamson and Fessler and colleagues described their initial clinical experience with this technique in 2001 and 2002, respectively. The technique was found to be safe and effective [105, 106]. Wang and colleagues described their initial experience and 2-year follow-up on short segment lateral mass fixation using a tubular retractor system [107, 108]. Their technique involved a midline incision followed by placement of tubular retractors that were directed rostrally and laterally ("up and out") in a trajectory very similar to that used for traditional open cervical lateral mass screw placement. The major limitation of this method remained the need for rod passage and the need for a mini-open exposure of the lateral masses [108]. Wang and colleagues also explored minimally invasive applications for cervical laminoplasty. They reported their initial cadaveric study in 2003, along with recent clinical experience documenting the technique's feasibility in 2008 [109, 110]. Recently, Ahmad and colleagues described their initial experience with percutaneous trans-facet screw instrumentation in the subaxial cervical spine. This technique is particularly attractive because it avoids the need for an interconnecting plate/rod. It has been used primarily to supplement anterior fusion surgeries where the risk of pseudoarthrosis or kyphosis is high [103].

Early clinical experiences with minimally invasive posterior approaches to the cervical spine are promising. However, these techniques are challenging and carry a steep learning curve. Ultimately, patient-driven outcome assessment and randomized, prospective studies will be needed for validation of these approaches.

Conclusion

The future for minimally invasive spine surgery appears promising. New technologies will allow surgeons to effectively perform more complex spinal procedures using techniques that minimize tissue injury. These procedures hold the promise of decreased iatrogenic soft tissue injury and approach-related morbidity while allowing the surgeon to perform the operation as effectively as the conventional open surgery.

Preliminary results suggest that many minimally invasive spinal procedures can be performed safely and effectively, and at this time long-term outcomes are starting to be reported in the literature. The long-term improvement of patient-derived outcomes has positive implications for cost-effectiveness of these techniques. Studies assessing cost savings and cost-effectiveness are essential, as rates of spine surgery have increased dramatically over the past decade, with the most dramatic increase noted for lumbar fusion [111]. In fact, recent studies have demonstrated the cost-effectiveness of minimally invasive lumbar fusion [112–114]. Although minimally invasive spinal techniques have a logical basis and are appealing to patient and surgeon alike, only prospectively conducted, long-term studies will clearly determine their advantages and disadvantages compared with conventional open surgeries.

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