Minimally Invasive Spine Surgery

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Minimally Invasive Thoracolumbar Spine Surgery

The first report of microdiscectomy utilizing the microscope was in 1967, which still involved open dissection of the paraspinal musculature and laminae [2]. In 1969, injection of the proteolytic enzyme chymopapain into the disc was used in a technique referred to as chemonucleolysis, resulting in the breakdown of macromolecules in the nucleus pulposus [3]. This was considered the first minimally invasive spine procedure, although it was not popularized at the time due to several reports of arachnoiditis and chemical discitis, resulting in several months of low back pain. In 1975, small self-retaining soft tissues retractors were introduced, allowing performance of microdiscectomy through a smaller window [4]. The use of laser technology in spine surgery was first reported in 1978 when it was used to excise spinal cord tumors, but it was not until 1984 that it was first used to treat lumbar disc disease [5].

A major milestone in the history of MISS was the development of tubular access and retractor systems. The first rudimentary application of this system was in 1991 [6]. Under biplanar fluoroscopic guidance, a cannula with a guide wire followed by a working sleeve with an outer diameter of 5.4 mm were introduced into the affected disc. The guide wire was then removed and "nucleus forceps" and high vacuum and irrigation were used to remove the disc material. This procedure was performed under local anesthesia, and usually took about 20 minutes.

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The tubular approach was further refined in 1997 with the introduction of the microendoscopic discectomy (MED) system, in which serial dilators were used to introduce a bigger tubular retractor, to which an endoscope is attached [7]. This technique did not gain immediate popularity initially, primarily due to the steep learning curve and surgeon unfamiliarity with the endoscope, which resulted in relatively high rate of unintended dural tears. With more experience, however, it was shown to be a reliable minimally invasive approach to microdiscectomies, even for large disc herniations. When compared with open microdiscectomy, the MED approach had equivalent long-term improvement in pain and disability but with less morbidity [8–11].

In the early 2000’s, the MED system evolved into the Microscopic Endoscopic Tubular Retractor System (METRx; developed by Medtronic Sofamor DaneK, Memphis, TN). Like MED, the METRx system also consists of a series of dilators and tubular retractors. One of the distinguishing features between the two systems is the incorporation of the operative microscope. The first application of the METRx technique was in lumbar microdiscectomies. Initial experience followed by several studies demonstrated excellent clinical results and cost effectiveness with this approach, particularly in terms of decreased blood loss, less tissue trauma, less post-operative pain, lower rates of surgical site infections, shorter hospital stays, and faster return to work [12–14]. This system was also found to be favorable in obese patients, which is a patient population that typically requires larger incisions and is more prone to post-operative infections [15].

Figure 20.1a–e show microdiscectomy using the METRx system. Figure 20.1a shows the paramedian approach to the lumbar spine using the tubular retractor. Figure 20.1b shows fluoroscopic confirmation of the tubular retractor position over the intended disc space. Figure 20.1c shows the view through the tubular retractor with the operative microscope. Figure 20.1d shows the small size of the incision needed for the procedure. Figure 20.1e shows the extracted large disc fragment.

The use of MISS techniques expanded to decompressive laminectomies, with the ability to perform bilateral decompression via a unilateral approach [16, 17]. Perhaps the most notable benefit of the minimally invasive approach to decompression is the preservation of the supporting structures in the lumbar spine, which has been shown to minimize post-operative instability and the need for fusion [18]. This is particularly important in patients with degenerative spondylolisthesis, in which minimally invasive decompression resulted in less progression of the slip and lower reoperation rates for secondary fusion [19].

The application of minimally invasive techniques to instrumentation represents the next major step in the evolution of MISS. In contemporary spine surgery, pedicle screw fixation has become the standard technique for instrumentation in the thoracolumbar spine. To expose the entry point of pedicle screws via an open approach, the the multifidus muscle has to be elevated and retracted off the laminae and facet joints. This results in atrophy of the muscles due to denervation from damage to the medial branch of the posterior rami as well as ischemic necrosis from prolonged retraction. Functionally, this is associated with increased post-operative pain and decreased truncal extensor muscle strength [20, 21].

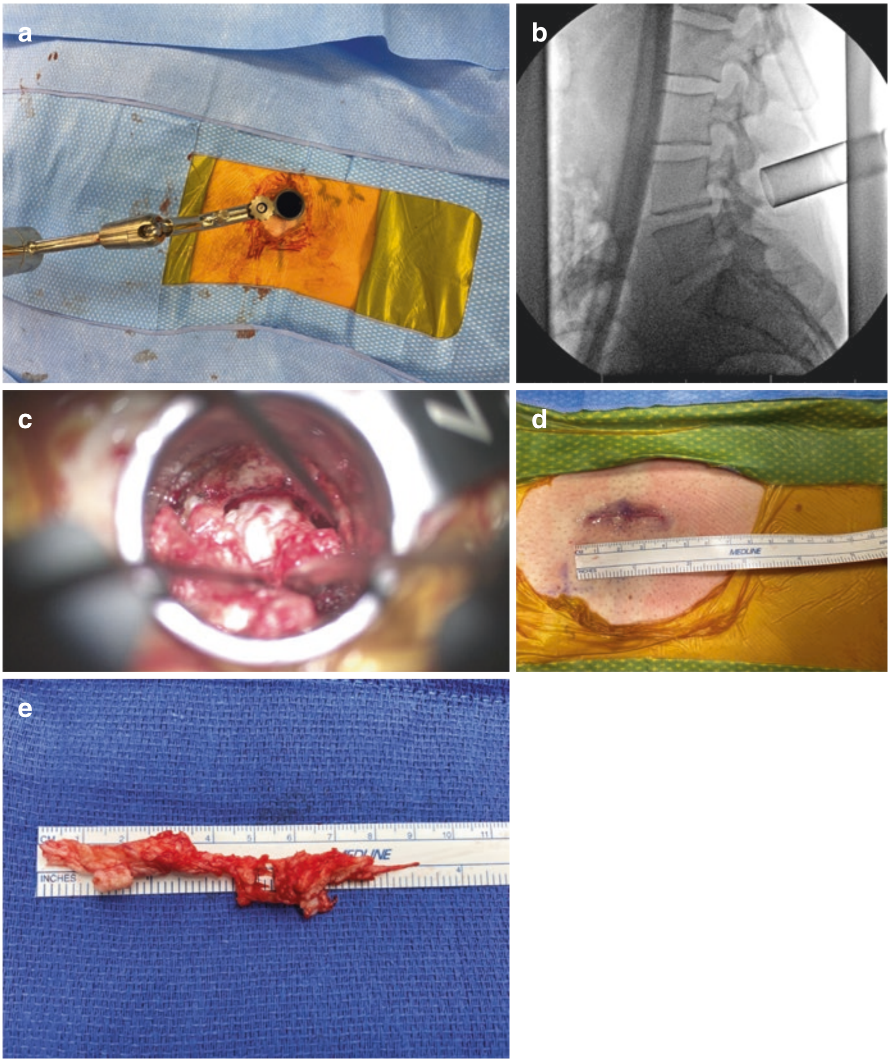

Fig. 20.1 (**a**) Paramedian approach to the lumbar spine using the tubular retractor. (**b**) Fluoroscopic confirmation of the tubular retractor position over the intended disc space. (**c**) View through the tubular retractor with the operative microscope. (**d**) Demonstration of the small size of the incision needed. (**e**) Extracted large disc fragment

To minimize soft tissue damage, percutaneous pedicle screw fixation was introduced in the early 2000's [22, 23]. Using this technique, the pedicle is cannulated percutaneously via a small stab incision through the skin and fascia, leaving the paraspinal musculature essentially intact. Rods are then fitted onto the screws in a subfascial fashion using one of several different systems. In thoracolumbar trauma, this technique was shown to be a feasible alternative to open fusion, with lower operative time, perioperative blood loss, surgical site infection, and pain [24, 25].

In addition to tubular retractors, percutaneous pedicle screw fixation has revolutionarized the field MISS, particularly for degenerative conditions. In 2002, the first minimally invasive posterior lumbar interbody fusion was reported, showing feasibility of achieving wide decompression with interbody fusion while minimizing iatrogenic damage [26]. In 2005, several studies reported success with minimally invasive transforaminal interbody fusion [27–29]. These early positive results were confirmed by several recent systematic analyses, demonstrating efficacy, safety, and cost effectiveness [30–33].

The next phase of MISS came in the form of anterolateral lumbar interbody fusion techniques. These techniques include the transposas (e.g. lateral), prepsoas (e.g. oblique), and anterior approaches [34]. The detailed differences among these approaches are beyond the scope of this chapter, but these approaches offer several advantages worth noting here. Since anterolateral approaches can be used as a standlone arthrodesis technique of the anterior lumbar spine, one of the major advantages is the complete avoidance of violating the paraspinal musculature, facet joints, and other posterior supporting ligaments, thus maintaining structural integrity of the lumbar spine. Even when posterior instrumentation is required, it is often achieved with percuatneous techniques that maintain the minimally invasive nature of the procedure. In patients with prior fusions presenting with adjacent segment disease requiring revision, an anterolateral approach can be utilized to treat that adjacent segment, thus avoiding re-opening the posterior incision and the morbidity associated with revision surgery [35, 36]. Another major advantage of minimally invasive anterolateral approaches is the ability to provide indirect decompression in patients with central or foraminal stenosis. By removing the collapsed disc and placing an interbody cage, the disc height is restored, which in turns increases foraminal height and minimizes “buckling” of the ligamentum flavum postrerior to the thecal sac [37–40].

Minimally Invasive Thoracic Spine Surgery

The thoracic spine is the most structuraly stable segment of the mobile spine because of the added support by the ribcage [41]. As a result, degenrative conditions are not as common in this region as they are in the cervical or lumbar spine. Nonetheless, several conditions, such as deformity, tumors, trauma, and infections, can affect the thoracic spine and necessitate surgery. From the late nineteenth century to the early twentieth century, surgery on the thoracic spine has predominantly consisted of dorsal decompression via laminectomy. The main limitation of that approach is the inability to achieve ventral decompression of the thecal sac or reach lesions involving the anterial thoracic spine due to the presence of the spinal cord [42]. To address that limitation, several posterolateral techniques were introduced as early as 1894 when the costotransversectomy approach was decribed to drain tuberculous paraspinal abscesses in patients with Pott’s disease [42]. In 1956, the anterolateral approach via thoracotomy was introduced to provide wide multilevel exposure to the anterior thoracic spine, which is sometimes necessary for correction of kypho-scoliotic defomities and tumor resections [43].

The posterolateral and transthoracic approaches to the thoracic spine have allowed for much better access to the ventral thoracic spine. However, as one can imagine, these can be very invasive procedures and can be associated with significant morbity. The reported complication rate for the transthoracic approach is as high as 39% whereas the complication rate for posterolateral approaches ranges between 15% and 17% [44]. Thus, the need for the incorporation of MISS techniques to this challenging region of the spine has become apparent.

One of the major advances in minimally invasive thoracic spine surgery is the incorporation of video-assisted thoracoscopic surgery (VATS) technology. This techonology was developed by cardiothoracic surgery in the early 1990's to supplant the traditional thoracotomy approaches to several intrathoracic pathologies [45]. The advantages of VATS over open thoracotomy were readily apparent—smaller incision, less acute and chronic pain, reduced length of hospital stay, and faster return to normal activities. Since 1991, the utility of VATS has been successfully demonstrated in treating thoracic disc herniations, anterior release for deformity corrections, corpectomies, and drainage of spinal abscesses, without the high morbidity associated with the traditional thoracotomy approach [46]. This procedure, however, is associated with a steep learning curve and requires specialized training and collaboration with thoracic surgeons [47].

With regard to posterolateral approaches, advances in minimally invasive techniques to the thoracic spine were developed in parallel with those employed in the lumbar spine. Rather than prolonged immobilization or open instrumented fusion, the percutaneous pedicle screw fixation technique has been successfully applied to internally stabilize fractures [48]. Similarly,the use of tubular retractor systems has made it possible to transform invasive procedures requiring long incisions and extensive dissection into much less invasive ones [49, 50].

Minimally Invasive Cervical Spine Surgery

Surgical approaches to the cervical spine have evolved significantly over the past few decades. Disorders of the cervical spine can be treated via an anterior approach as well as a posterior one. Anteriorly, disc herniations, traumatic injuries, and neoplasms involving the vertebral bodies have been treated with anterior cervical discectomy and fusion (ACDF). First introduced in 1955 and refined in 1958, ACDF offers a relatively minimally invasive approach to the anterior cervical spine [51]. It is performed through a small incision and without much iatrogenic tissue disruption as it takes advantage of the normal tissue planes in the neck.

Variations of the ACDF approach have been developed over the past two decades to make the procedure even less invasive. Cervical disc arthroplasty is an example of such variation which was popularized in the early 2000's [52]. It involves removal of the diseased disc and replacing it with an artificial disc implant that preserves segmental motion at that level. This procedure does not require placement of screws or plates and does not require the aggressive preparation of the endplates needed to promote arthrodesis. Furthermore, becasuse of the motion preservation and the minimal disruption to normal cervical spine biomechanics, some studies reported better long term outcomes compared to ACDF in terms of improved pain and lower incidence of reoperation for adjacent segment disease [53].

Similar to decompression of the thoracic and lumbar spine, laminectomy has been the gold standard for dorsal decompression of the neural elements in the cervical spine. Traditionally, open decompression and/or stabilization with screws/rods involve extensive muscular dissection and retraction, which has negative impact on the structral integrety of the spine. Postlaminectomy kyphosis is a well-documented long-term consequence of the disruption of the posterior supporting bony, ligamentous, and muscular structures, and is particularly improtant in patients with multilevel decompression and baseline reversal of normal cervical lordosis [54]. To minimze collateral iatrogenic damage, minimally invasive approaches to the posterior cervical spine were developed, the most prevalent of which is tubular microscopic or endoscopic laminoforaminotomy [55]. This procedure allows for decompression of the lateral thecal sac and exiting nerve root in patients with radiculopathy with minimal trauma to the posterior paraspinal musculature, and has been shown to reduce post-operative analgesic medication usage, intra-operative blood loss, and length of hospital stay when compared with the open approach [56]. Additionally, when compared with ACDF, minimally invasive laminoforamintomy was shown to be at least as efficacious as ACDF in treating radiculopathy while still maintaining a lower complication profile and reoperation rate [57].

With regard to fusion procedures, open approaches have remained the gold standard for instrumented posterolateral fixation of the axial and subaxial cervical spine. Nonetheless, few minimally invasive posterior fusion techniques are described in the literature. One example is C1–C2 instrumented fixation using tubular retractors [58]. The procedure is performed through bilateral 2 cm incisions that are 2 cm off the midline, and fluoroscopy is used for screw placement. Similarly, multilevel lateral mass screws can be placed using specialized tubular retractors with deep tissue expanders called “skirts” [59]. These procedures, however, are technically challenging and requires normal unaltered anatomy, comfort with open instrumentation and general minimally invasive techniques, and excellent fluoroscopic visualization.

Percutaneous facet joint instrumentation is another interesting example. The facetal distraction-fixation procedure was first reported in 2004 as an adjunct to screw/rod fixation for atlantoaxial instability [60]. It has then evolved to treat instability and degenerative pathologies in the axial and subaxial spine by “jamming” a metallic cage implant in the distracted joint either as a percutaneous standalone fixation technique or in combination with open lateral mass screw/rod systems [61]. This facetal distraction-fixation technique provides indirect decompression of the nerve root and confers segmental stability by promoting arthrodesis. Indeed, the fusion rate of the standalone technique after 2 years is up to 98.1%, with no segmental kyphosis, device failures, or reoperations [62]. Contraindications to this procedure are infections, tumors affecting the facet joint, traumatic facet injuries, and high grade listhesis [63].

Miscellaneous

There are other notable examples of MISS that do not fit within any of the above sections. One such example is sacroiliac (SI) joint fusion. The prevalence of sacroilitis in patients with chronic low back pain is reported to be up to 30% [64]. Nonetheless, it has remained an under-recognized problem in patients presenting with low back or buttock pain due to the significant overlap of symptoms and the lack of specific diagnostic tests or reliable physical exam findings [65]. Once the diagnosis is established, usually by a constellation of exam findings and diagnostic injections, surgical treatment can be offered to stabilize the joint if the patient fails a trial of therapeutic injections and/or radiofrequency denervation. Different surgical approaches to the SI joint have been described. The intra-pelvic anterior approach to the SI joint over the pelvic brim is one of the earliest approaches described in the literature, but it is an invasive procedure and access to the joint is limited by the iliac vessels and the S1 and S2 nerve roots [66]. To avoid the morbidity of the anterior approach, an open lateral trans-iliac subgluteal approach was developed, which minimized the possibility of direct injury to the major vessels and nerve roots [67]. Still, this also constituted an invasive approach, requiring dissection of the gluteal muscles and drilling a bony window in the iliac bone, entailing the possibility of indirect neurovasular injury with misguided screws or dowels across the ventromedial aspect of the joint.

Beginning in the early 2000's, minimally invasive SI joint fusion techniques have been introduced, utilizing fluoroscopic guidance to percutaneously place triangular or cylindrical implants across the joint through either a lateral transarticular approach or a posterior intraarticular approach [68, 69]. When compared with their open counterparts, minimnally invasive techniques demonstrate superior pain relief and decreased perioperative morbidity [70]. When compared to nonoperative management, SI joint fusion undoubtedly provides excellent long term outcomes in terms of improvement in pain, decreased opioid consumption, faster return to work, and improved quality of life [71, 72]. Currently, as progress is made in the diagnosis and treatment of sacroilitis, minimally invasive SI joint fusion is increasingly becoming an integral component in managing patients who have failed a trial of conservative management.

Vertebroplasty and kyphoplasty represent another major form of MISS. This procedure was initially described in 1987 in France [73]. In the mid 1990's, the procedure gained popularity in the United States, and its use has expanded to encompass osteoporotic fractures, pathologic fractures, and augmentation of weak vertebrae prior to surgery [74]. It is a minimally invasive procedure that is performed percutaneously under fluoroscopic guidance by inflating a balloon to restore height and injecting methyl methacrylate cement into the vertebral body through a transpedicular or parapedicular needle [75]. The most common indication for the procedure is osteoporotic compression fracture refractory to conservative management for at least 2 weeks. Another common indication is the treatment of metastases with or without adjucant surgery or radiation to not only relieve pain but also to maintain structural integrity in the setting of lytic vertebral body lesions. The procedure is very effective, with significant short and long term improvement in mobility, analgesic usage, pain at rest, and pain with activity [54].

Technological Advances in Minimally Invasive Spine Surgery

Image-guided surgery (IGS) has had a tremendous impact in the development and expansion of the field of MISS. Intra-operative imaging evolved from two-dimentional (2-D) fluoroscopy and plain films to more advanced three-dimentional (3-D) intra-operative navigation systems. The first application of a 3-D navigation system in spine surgery was reported in 1996 when a cranial neurosurgery navigation system utilizing pre-operative CT images was adapted to spine surgery [76]. This interactive navigation system demonstrated improved instrumentation accuracy and better intraoperative localization of important anatomic structures compared to traditional 2-D imaging methods. Building upon that technology, fluoroscopy-based navigation systems were developed, with the main advantage of offering "real time" intra-operative images rather than using images obtained pre-operatively [77–79]. Further advances led to the development of intra-operative CT-guided navigation systems (e.g. O-Arm, Medtronic Inc., Louisville, Colorado, USA), which currently remain the gold standard in intra-operative navigation in spine surgery. The newer low-dose CT-based systems allow for the rapid acquisition of optimal intra-operative imaging and precise navigated instrumentation, while still decreasing overall radiation exposure to surgical staff and decrreasing operative time in certain situations [80–82].

Another exciting example of the influx of technology into the field of spine surgery is the incorporation of robotic technology. Surgical robotic technology in general is divided into two categories: telesurgical robotic systems and robotic-assisted navigation (RAN) [83]. An example of the former is the Da Vinci robotic system (Intuitive Surgical Inc., Sunnyvale, CA, USA), through which the surgeon is able to perform the surgery from a command station with the robot handling all the instruments. This system is most commonly utilized in general surgical specialties; it is not FDA-approved for spine surgery and its role in spine surgery to date has been limited to few reports describing its usage for anterior exposure of the lumbar spine.

The latter category of robotic surgery is more relevant to the field of MISS. In RAN, the role of the robot is to provide guidance to the surgeon in placement of instrumentation utilizing pre- or intra-operatively obtained imaging. The first RAN system was developed in 2004 and later obtained FDA aproval for use in spine surgery [84]. The initial prototype utilized pre-operative CT scans merged with intra-operative fluoroscopy. It demonstrated high accuracy in pedicle screw placement and significantly reduced radiation exposure when compared to fluoroscopy-guided instrumentation [85]. As with any new technology, however, initial experience revealed a steep learning curve and occasional issues with accuracy due to issues with registration or excessive pressure from soft tissues or the surgeon on the robotic arm resulting in deviation from planned trajectory. Newer iterations of RAN improved upon the initial prototype, producing smaller robotic systems that are able to process information seamlessly, plan multiple trajectories simultaneously, detect drill skiving, and compensate for patient movement. With these recent refinements, accuracy of pedicle screw placement was as high as 99% and with minimal need to return to the operating room for malpositioned screws [86]. Nonetheless, robotic technology in spine surgery remains in its infancy, with ongoing studies about long term outcomes and cost-effectiveness compared to the more established technologies [87, 88].

Lastly, we will conclude this section with a discussion about augmented reality (AR) surgical navigation technology in spine surgery. With this technology, the surgeon, via wearable heads up display or the operative microscope, is able to have "x-ray" vision by superimposing a virtual picture onto the patient's physical anatomy. This technology has been applied not only in pedicle screw placement but also in other procedures such as tumor resections, deformity corrections, and vertebroplasty/kyphoplasty [89]. One advantage of AR over prior methods of IGS is the ability of the surgeon to maintain field of vision over the patient rather looking away from the surgical field onto a screen. Furthermore, AR provides an excellent educational tool outside of the operating room, allowing trainees to place virtual pedicle screws with haptic feedback [90]. Again, as is the case with robotics, AR still remains in a very early stage in its clinical application to spine surgery, and further studies are needed to validate its outcomes and cost-effectiveness.

Conclusion

Tremendous advances have been made in the field of minimally invasive spine surgery. With growing technology, spine surgery is gradually transforming away from the traditional open approaches that usually result in extensive collateral iatrogenic to more sleek approaches utilizing an armamentarium of new imaging and instrumentation tools. The overall end result of this paradim shift is less acute and chronic pain, minimal blood loss, shorter hospital stay, less radiation exposure, and faster return to normal function. The future of MISS is promising as current technologies are constantly being refined and newer advances are continuously being implemented and validated.

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