Minimally Invasive Spine Surgery

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Bilal B. Butt, Rakesh Patel, and Ilyas Aleem

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Abstract

This chapter explores the basic principles and concepts of minimally invasive spine surgery (MIS). It provides technical insight into how these procedures are performed safely. By utilizing MIS techniques, one can largely treat the same conditions, which historically have been treated in the open fashion. Both short- and long-term advantages will be discussed including but not limited to decreased blood loss, decreased postoperative pain, and faster return to baseline. The application of these methods to deformity correction surgery and interbody fusions will also be explored. The roles of navigation and robotics in this rapidly expanding field and how they

B. B. Butt · R. Patel · I. Aleem (✉)
Department of Orthopaedic Surgery, University of Michigan, Ann Arbor, MI, USA
e-mail: bbutt@med.umich.edu; Rockpatelmd@gmail.com; ialeem@med.umich.edu

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can be utilized to improve accuracy are investigated. This chapter is targeted toward junior faculty members, residents, midlevel providers, and other individuals who wish to expand their knowledge base on MIS.

Keywords

Minimally invasive surgery · MIS · Pedicle screws · MIS TLIF

What Is Minimally Invasive Spine Surgery (MIS)?

Minimally invasive spine surgery (MIS) strives to correct surgical pathology, which is typically treated with larger incisions and greater tissue destruction, with the goal of better short- and long-term patient outcomes. Although long-term benefits are debatable, the short-term benefits, including decreased blood loss, decreased postoperative pain, decreased hospital stays, and faster return to baseline, have been well established (Lombardi et al. 2014; Tullberg et al. 1993; Obenchain 1991; Shamji et al. 2015; Terman et al. 2014; Parajon and Hartl 2017; Costanzo et al. 2014). Additionally, MIS techniques have been shown to decrease both the direct and indirect costs associated with certain surgical procedures (Shamji et al. 2015). By decreasing operative time, blood transfusions, and length of stay, the direct cost is significantly impacted. Earlier return to work and fewer postoperative hospital visits significantly decrease indirect costs. The goal of this chapter is to present the reader with current MIS techniques as well as a brief insight into the future of MIS.

Advantages and Disadvantages of MIS

There are several advantages and disadvantages of MIS techniques. A steep learning curve is associated with the safe implementation of MIS into one's practice, resulting in a lower than expected adaptation of this technique. Numerous studies have demonstrated that the first 20–30 cases of a surgeon's implementation of MIS may be associated with higher rates of complications (Sclafani and Kim 2014; Shamji et al. 2015; Fujibayashi et al. 2017). In addition to the steep learning curve, another barrier to adaption of MIS techniques is increased radiation exposure to the surgeon due to reliance on fluoroscopy. However, this risk may be minimized with the usage of intraoperative navigation.

Though introduced several decades ago, MIS techniques have made significant progress recently due to numerous technological advancements which have resulted in a numerous advantages of a less invasive approach. In utilizing an MIS approach, there is no need to detach the paraspinal muscles from their insertions on the spinous processes as compared to open techniques, thus minimizing muscle dissection and stripping (Pishnamaz and Schemmann 2018). Muscle injury in spinal surgery correlates with the length of time and force of the muscle retraction (Kawaguchi et al. 1996). With prolonged retraction, capillary perfusion is decreased and leads to accelerated rates of muscle fiber degeneration secondary to changes in cellular metabolism. The mechanism of this degeneration and necrosis are not yet fully elucidated, but most of these changes are believed to be associated with destruction of the sarcolemma and subsequent mitochondrial damage (Heffner and Barron 1978). Postoperative MRIs have demonstrated decreased cross-sectional area of paraspinal muscle, supporting the idea of muscle fiber atrophy following open surgery (Bresnahan et al. 2017) (Fig. 1). Stevens and colleagues used high-definition MRI to study the multifidus muscle postoperatively in patients undergoing MIS TLIF vs open TLIF. They observed significant intermuscular and intramuscular edema at the 6-month mark in those patients undergoing open TLIF. In patients who underwent MIS TLIF, no edema was present and overall the muscle appeared normal (Stevens et al. 2006). Levels of creatine kinase have also been used as a marker for muscle fiber injury. Open techniques have been shown to have a direct correlation with postoperative rises in creatine kinase levels, as compared to MIS, which show lower levels of CK

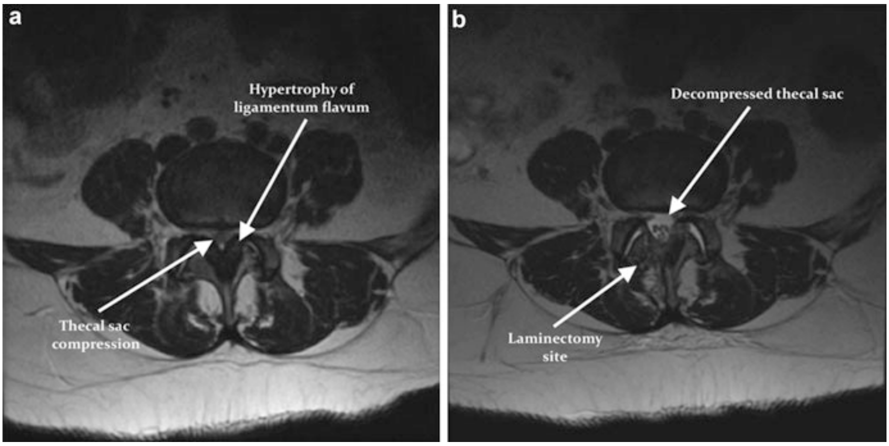

Fig. 1 (**a**–**b**) Comparison of pre-post op MIS laminectomy MRIs

(Wang et al. 2017). Cawley et al. were able to show that patients undergoing open surgery had abnormal postoperative EMG activation patterns in the lumbar multifidus as compared to those patients undergoing the same procedure via an MIS technique (Cawley et al. 2013). In evaluation of the sacrospinalis muscle using EMG, Wang et al. concluded that MIS TLIF was associated with reduced muscle damage as compared to open TLIF (Wang and FZ 2011). Newer data even suggest that with MIS techniques, the overall inflammatory state of the patient is decreased and this aids in shorter recovery periods as compared to open procedures (Lombardi et al. 2014). This is supported by lower levels of CRP, IL-6, and IL-10 following MIS procedures as compared to their conventional alternatives (Kim et al. 2006; Huang et al. 2005).

History of MIS

As a way to avoid excessive muscular retraction in spinal surgery, Wiltse et al. proposed a paraspinal sacrospinalis-splitting approach to the lumbar spine in 1968 (Wiltse 1973). The plane that Wiltse identified was an intermuscular plane between the multifidus muscle medially and the longissimus muscle laterally (Guiroy et al. 2018). Wiltse advocated that care must be taken to avoid overexposure of the vertebrae, as he had some concept of the negative consequences associated with excessive muscle stripping and damage. Because this approach utilizes an intermuscular plane, soft tissue trauma is minimized, and the posterior tension band of the spine and the supportive elements of the contralateral side are preserved (Anderson 2014). All of these taken together helped to improve patient outcomes following spinal surgery at the time.

MIS Discectomy

Disc herniations are painful and often debilitating conditions, which have a substantial impact on the function and quality of life of patients. There are also considerable social and economic impacts to society as most patients with disc herniations are of working age (Anderson et al. 2017). Given this, MIS discectomy may help mitigate some of the risks of surgery compared to open techniques and should be discussed with the patient if possible. Open surgery has been shown to be associated with longer operative times, longer incisions, increased bony resection, and increased retraction and damage to the paraspinal muscles as compared to MIS techniques (Ditsworth 1998; Rasouli et al. 2013; Alvi et al. 2018). MIS discectomy has been shown to have a shorter period of time off work, less opioid analgesia, less blood loss, and shorter hospital stays

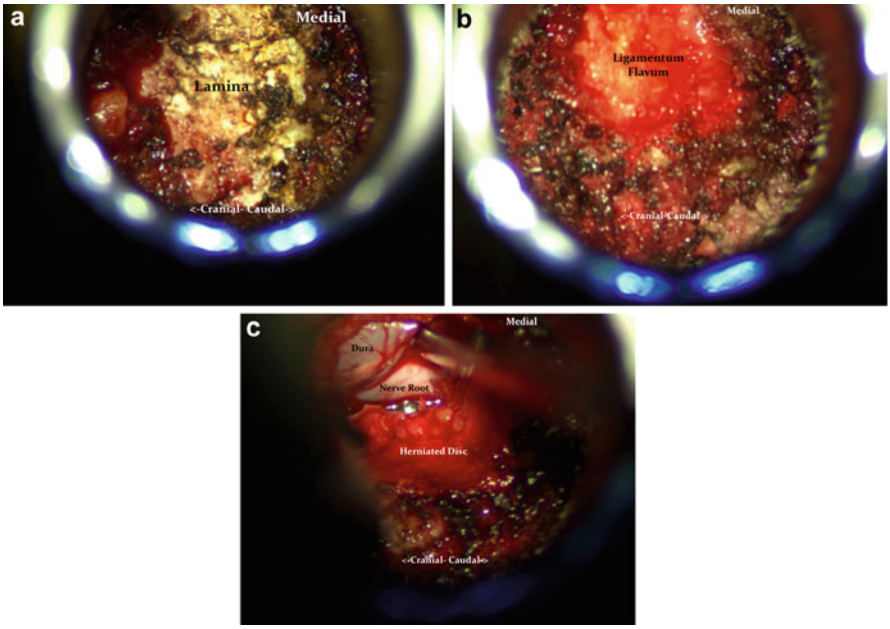

Fig. 2 (**a**–**c**) Intraoperative photos of discectomy through tubular dilator

(Tullberg et al. 1993; Kotil et al. 2007). It should be noted, however, that VAS scores both in short-term and long-term follow-up are essentially equivalent between groups of patients undergoing open procedures and those undergoing MIS procedures (Dasenbrock et al. 2012). Thus, both procedures ultimately decompress the neural elements and achieve pain relief.

As such, indications for MIS discectomy parallel those set forth for open procedures. Patients, who have failed conservative measures for a minimum of 6 weeks, have progressive motor weakness, or disabling pain can all be surgical candidates. As is standard, surgical indications should be evaluated on a case-by-case basis. The patient should always be included in the decision for surgery and appropriate informed consent should be obtained prior to surgery.

Obenchain described the first laparoscopic lumbar discectomy and was soon followed by Faubert and Caspar who published reports of lumbar percutaneous discectomy using a muscular retractor system in the early 1990s (Obenchain 1991; Faubert and Caspar 1991). This was the foundation by which Foley et al. built upon. Foley and colleagues used successive tubular dilators to achieve a desired diameter portal to which an endoscope was attached (Foley and Smith 1997). Foley's techniques were termed microendoscopic discectomy (MED) (Fig. 2).

Present day, usage of tubular retraction systems are common and are very much similar to Foley's initial description (Foley 2015). The patient should be positioned prone on a radiolucent spinal frame and prepped and draped in the usual fashion. Initially a 22-gauge spinal needle is introduced directed toward the facet joint. Careful attention is made to ensure that the needle does not aim midline, as this trajectory could puncture the dural sac and lead to a spinal fluid leak (Phillips et al. 2014). The location of the needle is confirmed using C-arm after obtaining orthogonal x-rays. Once the location is confirmed, the needle is removed, and a small, paraspinal incision is made, generally 2–2.5 cm lateral to midline. In cases where decompression of the contralateral is desired, the incision should be 3–4 cm lateral of the midline. If only an ipsilateral decompression is warranted, then the standard 2 cm from midline incision is sufficient. The incision should roughly be the same size as the

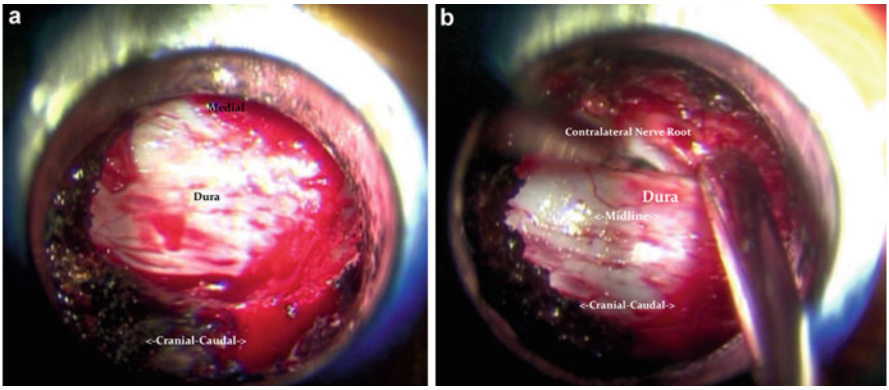

Fig. 3 (**a**–**b**) Intraoperative photos of Ipsilateral and contralateral laminectomy through tubular dilator

diameter of the intended tubular dilator (Phillips et al. 2014) (Fig. 3). Of note, in obese patients (BMIs >30), a more lateral incision may be necessary to obtain adequate visualization. There will be two distinct fascial layers present deep to skin incision. The superficial fascia represents that thoracodorsal fascial, and the deeper, thinner fascia represents that of the multifidus muscle (Schwender 2018). Both fascial incisions should extend slightly beyond that of the skin incision to allow for small adjustments by the surgeon. Once through the fascia of the multifidus, sequential tubular dilators are then used. The initial and smallest dilator is placed (docked) at the caudal edge of the lamina. Larger dilators are then placed over the initial dilator until an appropriately sized surgical window is created. Different procedures call for different diameter retractors. In the case of a microdiscectomy, 16–18 mm retractors are usually large enough for the procedure. The dilators are then removed and the retractor is placed in the muscular window. The retractor is then secured to the surgical table using a bracket mounted to the bed frame. Its location is then confirmed once again using fluoroscopy. Using a high-speed drill, a laminotomy is performed until the level of the ligamentum flavum. The flavum is then excised in a medial to lateral fashion using a Kerrison. The exposed nerve root is identified and protected and is gently retracted medially using a nerve root retractor. Using a bayonetted disc blade, an incision is made through the annulus fibrosis (Kimball and Yew 2013). Careful attention is paid to confirm the adequate decompression of the neural elements: thecal sac, nerve roots, and neural foramen. The surgical portal is then irrigated with saline, hemostasis is ensured, and the retractors are removed. The incision is closed in a layered, watertight fashion (Kulkarni et al. 2014).

MIS Laminectomy

A laminectomy in an appropriate selected patient can lead to significant reduction in neurogenic pain and its associated disability. It also has been shown to significantly improve patient-reported health-related quality of life (Shamji et al. 2015). Laminectomies are most often used to treat multilevel spinal stenosis, which is common in the aging population.

When evaluating the literature surrounding MIS laminectomy compared to open laminectomy, evidence supports that MIS procedures may be associated with less operative blood loss and shorter hospital stays (Terman et al. 2014). In a meta-analysis, Phan and Mobbs (2016) demonstrated that patients undergoing MIS laminectomies reported lower VAS scores as compared to the open approach, high rates of satisfaction, lower rates of blood loss, and thus lower rates of transfusions. They did note that reoperation rates were similar between both groups.

Much like the MIS discectomy, the MIS laminectomy utilizes the same overall approach.

The main differences that should be noted are the size of the tubular retractor is larger and there is more extensive bone and ligamentum flavum resection in order to obtain adequate neural decompression. Also it should be noted that the level of intended decompression will largely determine the necessary position for the tubular retractor. If the intended decompression is L1–L4, then the tubular retractor will be oriented more vertical and closer to the midline as compared to a decompression of L4–L5 or L5–S1 (Parajon and Hartl 2017). This is based on the anatomical bony structure of the vertebral bodies at those levels. Once the retractor is placed appropriately, a laminectomy is performed. The ligamentum flavum is then identified and removed. In cases where contralateral decompression is needed, the tube is repositioned medially; careful attention is needed as to not entrap soft tissue into the tube (Parajon and Hartl 2017). The table is then tilted away from the surgeon. The base of the spinous process is then drilled and undercut. The contralateral lamina is now removed using a high-speed drill and a Kerrison. Attention is now taken to the ligamentum flavum of the contralateral side and is removed. Some surgeons may benefit from utilization of a 90° Kerrison to aid them at this point. Once all of the flavum is removed, the table is then returned to its original position, hemostasis is ensured, and retractors are removed (Phillips et al. 2014; Watkins III and Watkins IV 2015).

MIS Transforaminal Lumbar Interbody Fusion (TLIF)

First described in early the 2000s, the TLIF provided an alternative to the standard posterior lumbar interbody fusion (PLIF) (Moskowitz 2002). A standard PLIF requires a midline incision through which exposure of the entire spinous process, bilateral lamina, and disc space is needed. This approach also places a fair amount of stress on the nerve roots as they are retracted out of the surgical field in order to garner access to the disc space. In the TILF a more lateral approach is made over the paraspinal muscles and directed toward the midline. This approach also allows for preservation of the contralateral side and requires less mobilization of the thecal sac and less risk of injury to a nerve root. There are also minimal retraction of the spinal nerves and decreased approach-related complications and morbidity as compared to the PLIF (Rosenberg and Mummaneni 2001). As a way to minimize the soft tissue trauma associated with open fusion procedures, Isaacs and colleagues described the minimally invasive transforaminal lumbar interbody fusion (MIS TLIF) (Hartl and Gelb 2017). In his original study, Issacs et al. compared their novel MIS TLIF techniques to standard single-level posterior interbody fusions at the same institutions. The authors concluded that patients undergoing the MIS TLIF had decreased hospital length of stay, decreased intraoperative blood loss, and received approximately 50% less postoperative narcotics as compared to the standard PLIF group (Isaacs et al. 2005). These outcomes were directly related the surgical approach in which normal tissue destruction was minimized. Common indications for a TLIF are foraminal stenosis, sagittal deformity, and central stenosis in patients with instability.

Following the same principles of tubular surgery described above, the MIS TLIF can be accomplished (Ozgur et al. 2006). Certain initial differences that should be highlighted are for one, the start point. The incision is initially made 4–5 cm lateral to the midline. This allows for an oblique entry into the spinal canal. As previously mentioned, the start point may have to be adjusted for larger patients. The desired visualized field for a TLIF is the inferior articulating facet joint of the level to be fused. In this, the capsule of the facet complex is entered and removed, and then the superior facet is resected down to the superior aspect of the pedicle (Hartl and Gelb 2017). The pedicle is then skeletonized. The ligamentum flavum is now exposed and can be removed in a piecemeal fashion using a Kerrison. The disc should now be visualized, and a discectomy is performed. Once the desired portion of disc is removed, the space is inspected to ensure adequate decompression. Bone graft and a structural implant are inserted to help preserve height and fuse the level. A MIS posterior fusion can sometimes be indicated. Because transverse processes are not exposed in the approach, the only surface area exposed following the decompression is the interbody space.

Lateral Interbody Fusion

First described by Pimenta at the Brazilian Spine Society Meeting in 2001 and via publication by Ozgur in the early 2000s, the lateral interbody fusion was a way to gain access into the lumbar spine via a minimally invasive far lateral approach. The procedure is performed via incisions that dissect down through the retroperitoneal fat and psoas muscle on to the vertebral body. The procedure provides good access of the anterior portion of the spine and accomplishes this without having to approach the spine via an anterior trans-peritoneal route (Ozgur et al. 2006). The use of a general surgeon is also avoided, as a spine surgeon can accomplish this minimally invasive method safely. In his report Ogzur notes that possible advantages of this procedure as compared to a standard anterior approach to the spine include no need for a general surgeon, no need to retract the aorta and IVC, simple operative technique as compared to laparoscopic methods, and avoidance complications of laparoscopic and open approaches. The entire procedure is performed under direct vision, and there is little to no impairment of the surgeon's depth perception. Serious complications of the standard anterior approach, damage to great vessels and superior hypogastric nerve plexus, are avoided because of the lateral entry. Some the most common complications associated with the lateral approach are sensory nerve injury and psoas muscle weakness (Fujibayashi et al. 2017).

Some of the main indications for patients to undergo a lateral interbody fusion are lumbar scoliosis, spondylolisthesis, foraminal or central stenosis, and according to newer reports corpectomy and stabilization in trauma patients (Isaacs et al. 2010). In this procedure, the patient is placed in the lateral decubitus position on a table that is able to flex. Attention is made to pad all bony prominences. The greater trochanter of the patient is located at the apex of the bend in the table. Of note, in choosing the entry side, a few considerations should be made. If the patient lacks a coronal plane deformity, then the preferred entry site is the left side of the patient, as the great vessels are located more anterior as compared to the right side (Pawar et al. 2015). If the patient has a coronal plane deformity, then the spine should be approached from the concavity of the lumbar curve. This allows for access to multiple levels of the spine, with a single skin incision. Once the desired side is chosen and the patient is positioned appropriately, the patient is secured to the table using tape or straps. Using fluoroscopy, true AP and lateral x-rays are taken, and the anterior and posterior borders of the vertebral body are identified. The patient is then prepped and draped in the usual sterile fashion (Fig. 4).

A skin incision is made in an oblique fashion from the anterior inferior caudal vertebral body to the posterior superior portion of the next adjacent vertebral body. The deep dissection continues through the subcutaneous fat and abdominal muscles to the retroperitoneal space. When dissecting through the abdominal muscles, attention is made to split muscles in line with the fibers. Between the internal oblique and the transverse abdominal muscle lie the iliohypogastric and ilioinguinal nerves, so care is made as to not cause excessive trauma to this region. Once at the retroperitoneal level, the surgeon can gently sweep the peritoneum anteriorly, lifting it off of the psoas muscle. Using intraoperative neuro-monitoring the fibers of the psoas muscle are splint in the anterior to middle third of the muscle (Ozgur et al. 2006). This location, coupled with neuro-monitoring, ensures that lumbar plexus nerve roots are not harmed. Once the level of disc space is reached, the location is confirmed with fluoroscopy. Now using tubular dilators, the surgical portal is enlarged until a self-retaining retractor is then introduced and secured. A discectomy is then performed in a standard fashion, and a structural implant is placed. Posteriorly, percutaneous pedicle screws can then be inserted as required.

Fig. 4 Image demonstrating patient positioning for lateral interbody fusion

Sacroiliac (SI) Joint Fusion

The SI joint is a complex synovial joint that connects the spine to the pelvis via many ligamentous and muscular attachments. Imbalance between any of these can lead to altered biomechanics, which often lead to pain and disability (Hungerford et al. 2003). Often this pain is overlooked as a pain generator as patients may report many non-focal symptoms such as back, groin, or gluteal pain. Prior trauma to the pelvic region, prior lumbar fusion, and large body habitus are all risk factors for SI joint dysfunction. Once the SI joint is isolated as the source of the pain, non-operative treatments are initially recommended. Treatments such as physical therapy, exercise, steroid injections, NSAIDs, and in some cases nerve ablation are all recommended prior to surgery. If these measures fail and the patient reports persistent pain lasting greater than 6 months or a sudden worsening of nerve function, then surgery would be indicated. Historically the SI fusion initially was performed without any screws via an incision made over the posterior superior iliac spine, articular cartilage was removed, and bone graft was placed (Smith-Petersen 1921). This method called for long periods of external stabilization by either bracing or casting, to ensure that fusion occurred. Internal fixation for SI fusions began to appear in the literature in the 1980s. This eliminated postoperative bracing, but due to the morbidity of the approach, extent of bone grafting, and lengthy hospital stays, this was not favored among patients (Moore 1997). With the advent of MIS approaches to the SI joint, the open procedure fell out of favor. A 2012 survey of spine surgeons globally noted that 85% of SI joint fusions were occurring via MIS techniques (Smith et al. 2013). In comparing open fusions to MIS SI joint fusions, MIS has shown to have shorter surgical times, less blood loss, shorter duration of hospital stays, and larger decreases in postoperative VAS scores (Smith et al. 2013).

For a MIS SI fusion, the patient is positioned prone on radiolucent spine operating room table. The patient is then prepped and draped in the usual sterile fashion. Using fluoroscopy, the affected joint is localized. Using a lateral view in which the sacral slopes are super-imposed, the appropriate trajectory is identified (Miller and Block 2014). Next a 2 cm lateral incision is made. The tissue is dissected and a dilator is advanced through the incision until it contacts bone. Its location can be confirmed with fluoroscopy. Next the dilator is removed and guide pin is drilled, first into the outer cortex of the ilium. Once this location is confirmed and the pin is perpendicular to the SI joint, it is advanced until it abuts the sacral cortex. The guide pin remains in place, and a 9 mm dilator is placed over it. Attention is paid to ensure that no soft tissue becomes entrapped in the dilator. Next a cannulated drill is passed over the guidewire and only the ilium is drilled. These shavings of cortex are saved on the back table for use later in grafting. Attention is now turned to preparing the SI joint for fusion. This is accomplished via insertion of a flexible decorticator (Kube). The cartilage is removed and the joint space is partially decorticated. The joint is then irrigated with saline, and dilators are reinserted. Bone graft is inserted into the cavity. A guidewire is then replaced and passed into the sacral cortex; its location is confirmed with C-arm. A cannulated screw is then placed over the guidewire and into the sacrum. Wound closure occurs in a watertight fashion.

Application of MIS to Deformity Correction

The previous sections discussed both the origins and the applications of MIS techniques to common spinal procedures: discectomy, laminectomies, and single-level fusions. In this section we will explore the literature surrounding the usage and benefits of MIS application to the field of adult deformity surgery (ADS). Historically deformity correction surgery in adults was associated with a major complication rate around 7.6% (Glassman et al. 2007) and an overall complication rate as high as 70% (Anand et al. 2014a). Major patient risk factors for complications are a sagittal vertical axis (SVA) great than 4 cm, age greater than 60 years old, and more than three medical comorbidities (Auerbach et al. 2016). As is the case with other procedures in spinal surgery, the overall goals of deformity surgery are to decompress the neural elements that are being impinged and establish/restore the global sagittal alignment. It has been demonstrated in great detail that kyphosis is poorly tolerated in lumbar region of the spine and has a direct correlation with the severity of patient-reported symptoms (Glassman et al. 2004). In attempting to measure outcomes following major ADS, Lafage et al. (2009) noted that both SVA and pelvic tilt as a measure of pelvic position have the highest correlation with health-related quality of life. Failure to restore a SVA <50 mm and a pelvic tilt less than 20° has been show to be associated with poor clinical outcomes. These goals can now be accomplished using the MIS techniques previously described and in some instances have better patient outcomes than conventional open procedures. Each clinical scenario is unique and requires a thoughtful and methodical process in planning for surgery. While MIS techniques are often sufficient to accomplish the goal, at times, there is a mix of MIS procedures and open surgery, termed hybrid surgery.

Percutaneous pedicle screw fixation's (PPSF) role in spinal deformity and spine trauma has been shown to be a safe and efficacious alternative to open surgery. Briefly, in this application, the patient is positioned prone on a radiolucent spine table, with bony prominences padded. The type of intraoperative imaging used is at the discretion of the surgeon as both navigation and fluoroscopy have been shown to be safe for pedicle screw placement (Park et al. 2010). This overview details usage of intraoperative biplanar fluoroscopy. X-rays are taken in the AP plane prior to any incisions to ensure that the superior endplate is flat (Anderson et al. 2007) and the pedicle-spinous process interface form an imaginary inverted "V." In the lateral view, careful attention is made to ensure that a single flat superior endplate and only a single pedicle shadow are identified. In obtaining orthogonal views, the relative positions of landmarks are identified (Fig. 5) (Aleem et al. 2017). An incision is then made approximately 4.5 cm lateral to the pedicle border. The fascia is incised and blunt dissection is used to obtain access to the junction between the transverse process and facet. A Jamshidi needle is then used to violate the dorsal pedicle in a lateral to medial fashion. Using AP and lateral imaging, the Jamshidi is advanced to the posterior cortex of the

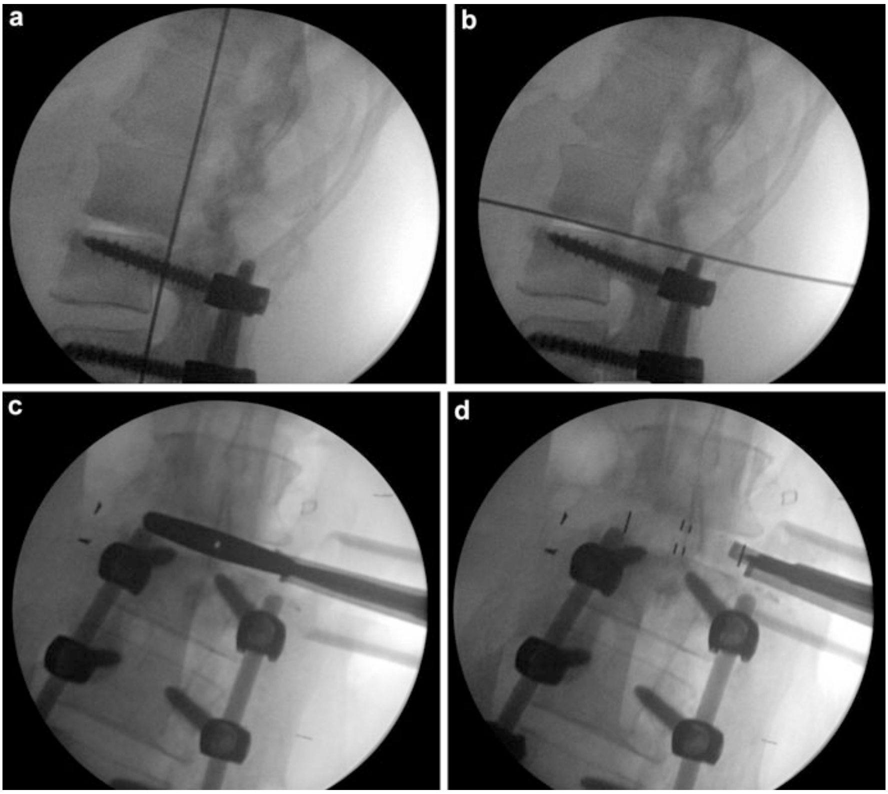

Fig. 5 (**a**–**d**) Intraoperative fluoroscopic images demonstrating level confirmation, endplate preparation, and implant plantation

pedicle (Figs. 6 and 7). The needle should be located in the center of the pedicle on lateral imaging, and it should never cross the medial border of the pedicle on AP imaging. Once in a satisfactory location, the needle is removed and replaced with a guidewire. A tap is used over the guidewire to expand the cortical opening. The guidewire should not be advanced beyond its initial placement, as this could potentially injure the great vessels located deep to it. Once tapping is completed, the tap is removed and replaced with a cannulated pedicle screw (Fig. 8). This process is then repeated, as indicated by the pathology. Once all screws have been placed, a rod is introduced usually from the most proximal screw's incision, and the desired reduction is performed. Aleem et al. described the technique of MIS screw fixation in detail (Fig. 9).

In his study Tinelli et al. demonstrated that using a MIS system in the setting of spinal trauma, his group was able to accurately place almost 98% of 682 pedicle screws in 131 fractures. The remaining 2% of screws were suboptimally placed, but not to the extent where revision surgery was necessary (Tinelli et al. 2014). Anand et al. were able to show that correction of adult lumbar degenerative scoliosis could be corrected with PPSF. He reported that multi-segment spinal corrections could be performed with less blood loss and less morbidity than open corrections (Anand et al. 2008).

Intraoperative fluoroscopy is a necessity in most cases when attempting PPSF in patients with deformity. For proper screw placement, it is imperative that both tilting view and wig-wag views are obtained if the case calls for it. As a technical note, one must ensure that one is orthogonal to the targeted pedicle to ensure proper location. If the operative case is not technically demanding and the surgeon is

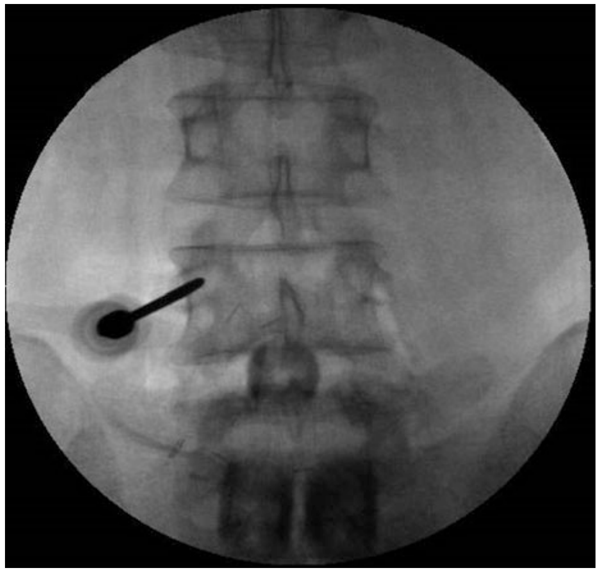

Fig. 6 AP image showing Jamshidi needle docked at start point on lateral edge of the pedicle at roughly the 9 o'clock position

Fig. 7 Lateral fluoroscopic image showing Jamshidi needled in center of pedicle

experienced enough, use of a single anteroposterior C-arm can be sufficient for proper screw placement. Ahmad and Wang (2014) demonstrated this, when 410 pedicle screws were placed in patients with at least 10° of axial rotation. He noted that he had 15 grade 1 violations, 6 grade 2 violations, and 8 grade 3 violations and only 2 screws were required to be revised. Of note the Gertzbein classification is most often used when discussing pedicle screw placement and location relative its medial or lateral wall. There are four grades in the classification ranging from 0 to 3. Grade 0 indicates that there is no breech of pedicle; grade 1, <2 mm breech; grade 2, 2–4 mm breech; and grade 3, >4 mm breech of the pedicle.

Fig. 8 Lateral fluoroscopic image showing pedicle screws with attachments

Fig. 9 Lateral fluoroscopic image showing rod capture in all screw heads

Role of Lateral Interbody Fusions

Lateral MIS approaches to the spine have numerous advantages compared to anterior approaches and however may be limited in their ability to sufficiently correct sagittal deformities in adults in isolation (Costanzo et al. 2014). In his systematic review, Costanzo et al. looked at the role of MIS lateral lumbar interbody fusions in sagittal balance and spinal deformity. He concluded that there is no clear answer with regard to how well MIS can correct sagittal balance and noted that open posterior osteotomies would continue to be the gold standard in sagittal balance correction (Costanzo et al. 2014). Acosta et al. performed a retrospective radiographic study looking at changes in coronal and sagittal plane alignments following lateral interbody fusions. Statistical improvements in the visual analog scale (VAS), the Oswestry Disability Indices (ODI), and the coronal Cobb angle were noted; however, no statistically significant change in the overall sagittal alignment was identified by a postoperative SVA measurements. They concluded that direct lateral interbody fusions alone are insufficient to correct for sagittal imbalance (Acosta et al. 2011). Deukmedjian et al. evaluated a novel technique for attempting to restore a normal SVA. In their study, they utilized a MIS lateral approach to first release the anterior longitudinal ligament and place a 30° hyperlordotic cage. Following this, percutaneous pedicle screws were placed posteriorly to help stabilize the construct. This resulted in a 17° segmental lordosis increase per level as well as an overall SVA decrease of 49 mm and a 7° pelvic tilt (Deukmedjian et al. 2012). Manwaring noted that a two-stage MIS procedure was comparable to Smith-Peterson osteotomies (SPO), because of its ability of providing disc height and correcting coronal imbalance (Manwaring et al. 2014). The first stage of the procedure involved lateral interbody fusions with or without anterior column releases (ACR). The second stage involved PPSF. A 12° improcvement in segmental lordosis and a 31 mm improvement in SVA per ACR level released were noted. Anand et al. have since adopted these principles of staged MIS procedures and proposed a protocol for MIS correction of adult spinal deformity (Anand et al. 2017). Much like Manwaring, Anand proposed that a lateral interbody fusion should occur in the first stage, with or without an ACR. He reports that avoiding an open surgery can avoid potentially serious postoperative complications.

Wang et al. (2014) described the ceiling effects for deformity correction of three different spinal surgery techniques: stand-alone (lateral MIS procedure), circumferential MIS (combined lateral with posterior), and hybrid procedures. The authors note that the ceiling effect in the coronal plane for all three procedures were as follows: 23° for stand-alone, 34 for cMIS, and 55° for the hybrid procedure. A statically significant alteration in the SVA occurred only in the hybrid procedure group, but this was overshadowed by high rates of complications in the hybrid group. Anand et al. (2014b) previously reported that the max SVA correction obtainable is 10 mm utilizing MIS techniques without osteotomies.

Limitations of MIS in ADS

As already noted, not all patients can or should undergo a MIS procedure. The decision to undergo a MIS procedure is ultimately left up to the shared decision-making of the surgeon as well as the patient. The goal should be to safely address surgical pathology and provide the best clinical outcome for the patient. In cases where the decision to proceed with a MIS procedure for ADS is made, some important patient factors should be considered, such as presenting symptoms, physical exam findings, and radiographic findings. Utilizing MIS in deformity surgery presents some unique limitations such as limited sagittal correction, decreased ability for in situ bending and compression, concern for sub-optimal correction, and pseudoarthrosis if interbody fusions are not performed. Since MIS procedures contain some level of a learning curve, inexperienced surgeons are likely to have increased operative times and increased cost of service as well as potentially increased radiation exposure to the patient and surgical team.

As a way to help surgeons select patients that can possibly benefit from MIS, the International Spine Study Group (ISSG) published a rational framework for decision-making in 2014. In this algorithm radiographic parameters are used to guide decision-making. The parameters used in the decision-making tree are SVA, PT, LL-PI mismatch, coronal Cobb angle, curve flexibility, and amount of listhesis. At its core the algorithm is based upon the idea that MIS is limited in its ability to treat sagittal plane deformities (Mummaneni et al. 2014).

Role of Navigation in MIS

As surgical technologies continue to advance, their contributions to surgical procedures are continually investigated. In the last 20 years, image guidance and navigation have come a long way in assisting the surgeon in accurate and safe positioning of hardware. Tajsic et al. (2018) evaluated and compared C-arm navigated, O-arm navigated, and conventional 2D fluoroscopy-assisted MIS techniques. Outcomes that were analyzed included operating time, radiation exposure, and the accuracy of pedicle screw placements. They concluded that pedicle screws placed with the assistance of the O-arm had the lowest rate of malpositioning (1.23%) and screws placed with 2D fluoroscopy were misplaced 5.16% of the time. However, O-arm usage was associated with highest rate of single image radiation exposure as compared to the other two modalities. Among all three modalities, operating room time was comparable. They concluded that given increased accuracy of pedicle screw placement, acceptable doses of overall radiation exposure, and comparable operating room time, the O-arm is the best form of intra-op navigation. Other studies have validated the usage of O-arm in MIS surgeries (Kleck et al. 2018; Chachan et al. 2018).

Robotics in MIS

As surgeons attempt to tackle more complex cases in the aging population, the indications for surgical fixation continue to evolve. As such, methods of attempting to reduce overall radiation to the patient and surgical team also evolve. The use of robotic-assisted pedicle screw placements has been discussed in the literature as a way to circumvent excessive intra-op radiation exposure. To our knowledge there has been only one randomized controlled trial comparing MIS robotics to open fluoroscopic-guided posterior lumbar interbody fusion (Hyun et al. 2017). The average per-screw radiation in the robotic-assisted surgeries was 37.5% of the per-screw exposure in the fluoroscopic group. Over all there was a mean reduction in radiation of 62.5% in the group undergoing robotic-assisted surgery. The results of the study are promising, but further data is needed to validate the routine use of robotics in MIS spinal surgeries.

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