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The evolution of minimally invasive spine surgery

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The field of minimally invasive spine surgery (MISS) has rapidly evolved over the past 3 decades. This review follows the evolution of techniques and principles that have led to significant advances in the field. While still representing only a subset of spine surgeries, MISS's goals of reducing soft-tissue trauma and mitigating the morbidity of surgery are being realized, translating into more rapid recovery, lower infection rates, and higher cost savings. Future advances in technology and techniques can be anticipated.

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KEYWORDS minimally invasive; cost; economic; spine; percutaneous; XLIF; TLIF; endoscopic

The field of spinal surgery has advanced significantly over the past half century. Along with the proliferation of techniques and technologies in general, there has been a concomitant movement to reduce the morbidity of surgery. Minimally invasive surgical (MIS) approaches have thus been popularized, with its core principles being the following: 1) to minimize the collateral damage, 2) to preserve the normal anatomy, and 3) to reduce the overall stress to the patient, all while achieving the same surgical goals as open surgery.

The roots in minimally invasive spine surgery (MISS) are based primarily on technique modifications. The Williams microdiscectomy, described in 1978, revolutionized MISS by starting the evolution of lumbar discectomy from an open surgery through a 6-inch incision to a microsurgical approach through as small an opening as possible.[68] The Wiltse approach, described in 1968, was revolutionary insomuch as the dissection in the spine was achieved *between* muscular planes, as opposed to through the soft-tissue envelope or the subperiosteal plane.[69] Subsequent developments have heavily leveraged new technologies, including enhanced retraction, fixation, biologics, visualization, monitoring, and navigation, further disrupting the landscape (Fig. 1).

However, it is instructive to first pose the question of "What is minimally invasive spine surgery?" Is it:

- A technique?
- A technology?
- A product?
- A surgical approach?
- A marketing ploy?
- A surgical philosophy?
- A systems-based approach for minimizing the overall impact of surgery?

In this review we retrace the history and evolution of MISS and attempt to highlight the major breakthroughs in the field.

MISS for Neural Decompression

One of the principal goals and indications for spinal surgery is decompression of the neural elements. As such, MISS has its roots here. Unlike open spine surgical procedures where the surgeon has the luxury of wide exposure to identify anatomy as well as multiple trajectories for tissue manipulation, an MIS approach by definition is more restrictive. The compromise between finding a surgical corridor that provides a large enough window to perform decompression while being minimally disruptive has been a perpetual challenge in MISS.

Microdiscectomy

The concept of microscopic discectomy introduced by Williams[68] was the precursor to the modern microdiscectomy in use today. Reducing soft-tissue dissection resulted in less postoperative back pain for patients; using the

ABBREVIATIONS MIS = minimally invasive surgical; MISS = minimally invasive spine surgery; TLIF = transforaminal lumbar interbody fusion.
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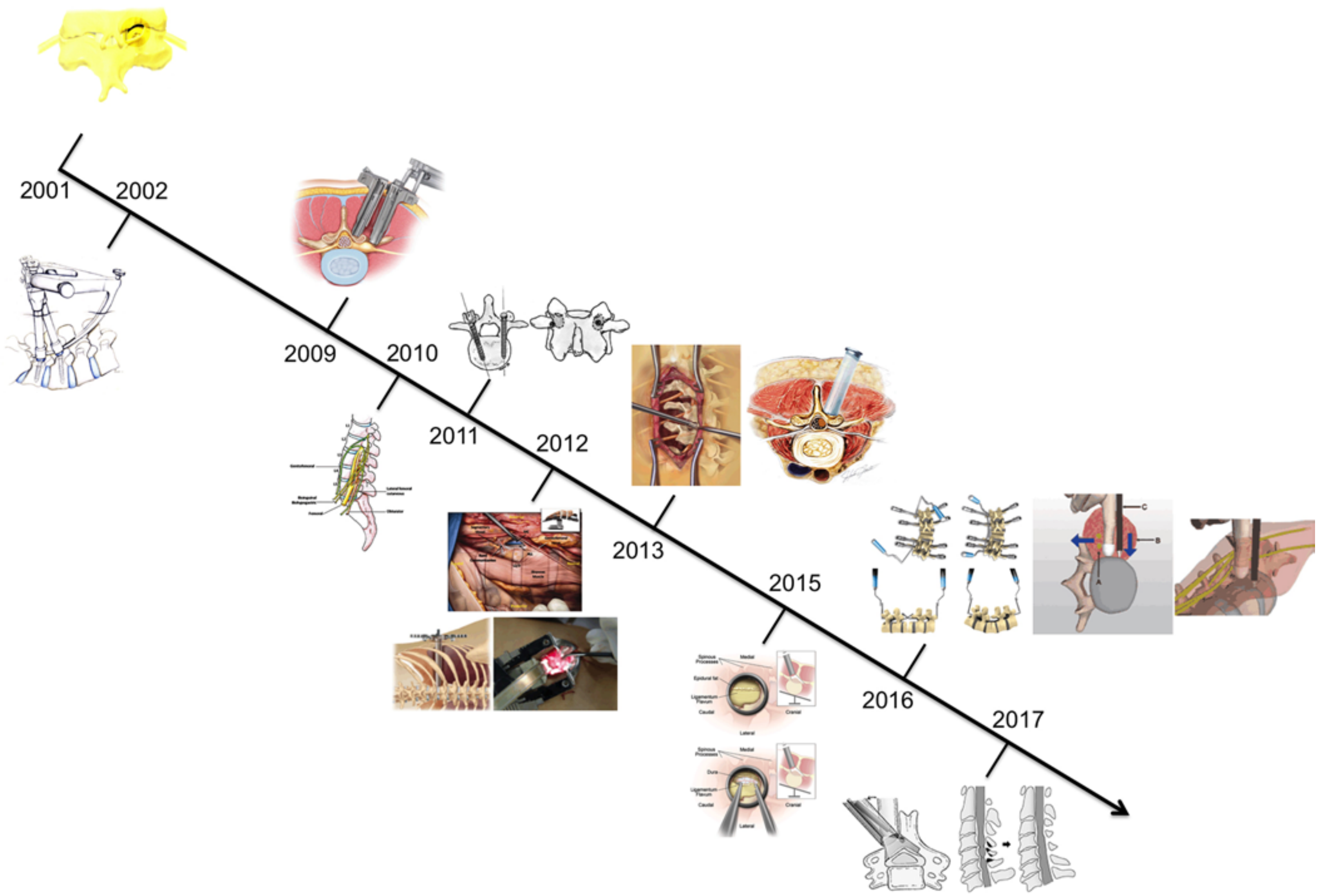

FIG. 1. The *Journal of Neurosurgery: Spine* has been a conduit for disseminating innovative technological breakthroughs in MISS. This is a list of cover art in the journal from 2001 to 2017 that highlighted techniques in MISS. Copyright American Association of Neurological Surgeons (Figs. from 2001, 2002, 2009, 2010, 2011, 2012 [upper and lower figures], 2013 [left figure], and 2016 [right figure]); Andre Nozokou (2013 [right figure]); Roger Härtl (2015); Roberto Suazo (2016 [left figure]); and Akihito Minamide (2017). Published with permission. Figure is available in color online only.

operating microscope allowed narrowing of the surgical corridor with enhanced illumination and magnified visualization. Smaller surgical tools with gentler manipulation of dura and nerve roots soon followed, which lowered surgical complications such as durotomy, nerve root injury, and discitis.[31] This paradigm shift continued with the application of tubular retractor technology and endoscopic surgery described below.

Muscle-Sparing Approaches

The need for paraspinal muscle dissection to gain surgical access frustrated spinal surgeons and patients alike. The effects of extensive subperiosteal stripping and prolonged retraction of the soft-tissue envelope are significant. Ischemic necrosis of the paraspinal muscles and chronic back pain can be seen in patients who undergo spinal surgery. Wiltse (Fig. 2B) and his colleagues innovated a unique approach that involved muscle splitting as opposed to subperiosteal stripping to achieve the same exposure.[69] The procedure involved "longitudinal separation of the sacrospinalis group between the multifidus and longissimus" to bluntly gain access to the posterior elements of the spine without cutting any muscle. Wiltse continued to apply this principle of muscle-sparing technique to perform far-lateral discectomy, insertion of pedicle screws, and ipsi-contralateral decompression in lumbar spine.[70] While not advocating for a small incision, Wiltse laid the groundwork and philosophical basis for MISS.

The Transforaminal Route

The transforaminal corridor to the lumbar spine is frequently used by surgeons, interventional radiologists, and pain physicians. This corridor is bound by the existing nerve root superiorly, superior endplate of caudal vertebral body inferiorly, and facet joint root medially. First described by Parviz Kambin (Fig. 2A) in 1973, the transforaminal access has been the workhorse for tackling a variety of pathologies that affect the lumbar spine. Initially he began to experiment with percutaneous posterolateral access to the spine to treat herniated discs at L3–4 and L4–5. Kambin described his surgical technique in detail, making an incision 8 to 9 cm off the midline and inserting a cannula with a converging angle of 35° to gain access to the disc space. This approach was aided by fluoroscopy,

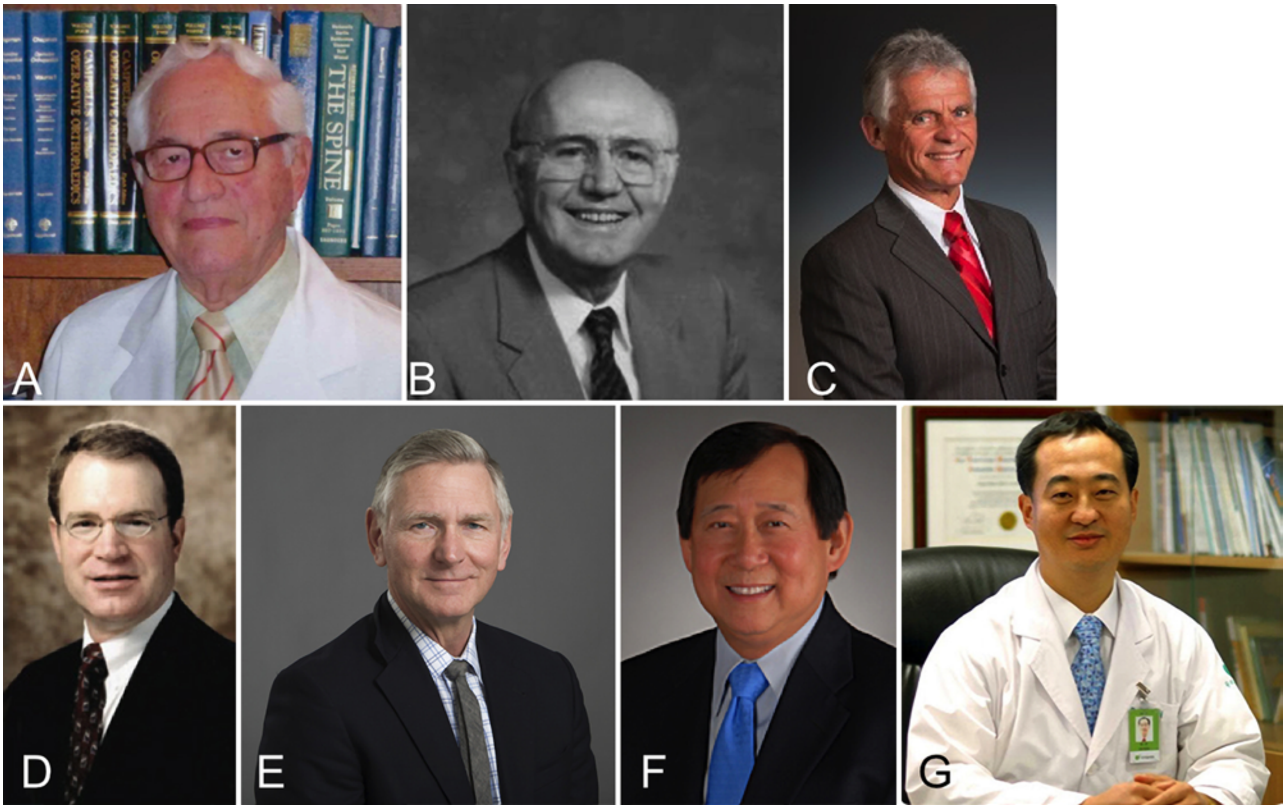

FIG. 2. Prominent figures in MIS spine surgery. **A:** Parviz Kambin (source: https://upload.wikimedia.org/wikipedia/commons/8/8a/Dr._Parviz_Kambin.jpg). **B:** Leon L. Wiltse (source: http://www.burtonreport.com/wp-content/uploads/2016/01/Wiltse200.gif). **C:** Luiz Pimenta (source: https://www.lateralaccess.org/assets/headshots/150 × 225-Luiz-Pimenta.jpg). **D:** Kevin T. Foley (source: http://www.truevisionsys.com/testimonials-neuro.html). **E:** Richard G. Fessler (source: https://www.nref.org/en/Ways-to-Give/Honor-Your-Mentor-Funds/Richard-G-Fessler-Fund). **F:** Anthony T. Yeung (source: https://www.sciatica.com/doctors/anthony-t-yeung-m-d/). **G:** Gun Choi (source: http://wooridul-ph.com/templates//inc/images/about/img_Dr.jpg). Copyright Jds319 (panel A, license type: CC BY-SA 4.0 [https://creativecommons.org/licenses/by-sa/4.0/]); Charles V. Burton (panel B); Society of Lateral Access Surgery (panel C); TrueVision Systems, Inc., 2018 (panel D); Neurosurgery Research & Education Foundation (panel E); Anthony T. Yeung (panel F); and Wooridul Hospital (panel G). Published with permission. Figure is available in color online only.

which in and of itself was unusual during that era, and was the predecessor to modern techniques that are dependent on technology (as opposed to direct visualization) for localization. By passing the cannula into the intervertebral disc, herniated disc fragments were delivered into the working cannula, through which disc fragments were aspirated by applying negative pressure. He concluded that complications such as "postoperative bleeding, perineural scar formation, and reherniation through the posterior fenestration" that are often associated with midline laminectomy and discectomy are avoided through his approach. Kambin continued to treat lumbar disc pathology through a transforaminal corridor, and would later publish his results regarding 100 patients with an 87% success rate with a transforaminal approach.[26,27]

Tubular Retractor Technology

One of the technological developments that has become in some minds synonymous with MISS has been tubular retractors. Through fixed or expandable retractors, MISS gained popularity as the more conventional microsurgical techniques using drills, Kerrison rongeurs, and nerve root retractors could be applied in a similar manner to open surgery. An early predecessor to this was Faubert and Caspar's report of a "percutaneous" microdiscectomy at the L4–5 level through a paramedian approach.[14]

In 1999, Foley (Fig. 2D) and Smith reported their experience of microendoscopic discectomy for far-lateral disc herniation in 11 consecutive patients using a tubular retractor and disposable endoscope. They described docking the initial dilator at "the junction of the cephalad transverse process and the pars," and through a 16-mm-diameter tubular retractor, decompression of the exiting nerve root was performed by removing the superior articular process with a Kerrison rongeur and high-speed drill.[17] While still used in East Asia, this technique fell out of favor due to high complication rates, in large part due to surgeon disorientation.[33,72]

A modification of this technique using potentially larger ports and a microscope instead of the endoscope led to the first modern wave of MISS acceptance. Fessler (Fig. 2E) and Khoo later applied these microendoscopic techniques to cervical foraminotomy in cadaveric specimens[19] and subsequently in clinical settings in 2002.[15] They concluded that tubular microendoscopic foraminotomy in the cervical spine yielded in equivalent clinical outcomes but resulted in less blood loss, shorter hospital stay, and less narcotic usage than open cervical foraminotomy.

With integration of the microscope and METRx tubular system, a paramedian tubular approach gained popularity with minimally invasive spine surgeons, and a flurry of reports emerged for lumbar discectomy, ipsi-contralateral central canal decompression, thoracic discectomy, tumor removal, infection treatment, etc.[20,21,42,43,67] Advantages of the paramedian tubular approach in comparison to the transforaminal approach included wider exposure, ability to perform wider bony decompression, and bimanual access.

Endoscopic Techniques

Coincident with the proliferation of tubular techniques, other surgeons advanced and refined working-channel endoscopic surgery. Improvements in glass-rod endoscope technology, digital image processing, and high-definition video all helped fuel these advancements. The obvious advantages of working-channel endoscopy was the reduction of the surgical corridor to less than 10 mm, but restrictions in tissue manipulation and visualization were part of that compromise.

Forst and Hausmann were the first to introduce a modified endoscopic camera through the working cannula through which they were able to examine the intervertebral disc space.[18] Schreiber and Suezawa began to perform nucleotomy under continuous endoscopic visualization, and reported successful outcomes in 72.5% of patients who had a herniated lumbar disc.[49] Kambin and Zhou reported their experience with lumbar arthroscopic microdiscectomy and lateral recess decompression with the use of forceps and trephines.[28] In 2005, Schubert and Hoogland described a “foraminoplasty” technique in which the working angle through the Kambin’s triangle is expanded by removing the ventral portion of the superior articular process with reamers.[50] Yeung and Tsou, Ruetten et al., and Jasper et al. reported successful endoscopic decompression of foraminal pathology (Fig. 2).[25,46,47,73]

Various subtle but important modifications to the transforaminal access corridor were developed, but limitations to central canal access persisted. Thus, the interlaminar route was developed.[5] The interlaminar approach allowed for paracentral and central (midline) lumbar discectomy, and the technique now has been modified to allow for lumbar stenosis decompression with partial facetectomy and ligamentum flavectomy, all through an 8-mm incision.[47] Posterior cervical foraminotomy[76] and thoracic spinal discectomy have now been recently added as working-channel endoscopic procedures in experienced hands.[45] Most recently, East Asian surgeons have been developing biportal methods for endoscopic decompression, using a method more similar to what is done in orthopedic joint/sports surgery and laparoscopic general surgery.

Many reasons exist for the divergent evolutionary path of working-channel endoscopy when comparing the US to East Asia. These include: 1) lack of US billing codes for endoscopic work, 2) poor reimbursement for these procedures, 3) differences in capital equipment purchasing power between nations, leading to a dearth of microscopes in the developing world, 4) lack of interest by major US medical device manufacturers, and 5) philosophical differences in the goals of spinal surgery

MISS for Spinal Fixation and Fusion

Advancements in spinal instrumentation have played a critical parallel and additive role with decompressive techniques in expanding the armamentarium of MISS. Michele and Krueger first described the pedicle screw fixation technique in 1949, which became a standard for achieving spinal stabilization.[1] However, open methods for fixation and fusion had previously required extensive exposure of the bony anatomy to allow for anatomical visualization, access to screw entry points, and preparation of bone grafting recipient site. Several major developments (which were not confined to the realm of MISS) have made possible the myriad of complex MISS options available today. Some of the major developments can be categorized as follows:

- The popularization of interbody (as opposed to posterolateral) fusion, which does not require as extensive exposure of the bony anatomy and allows for anterior corrective forces and indirect decompression
- An acceptance of intraoperative imaging (both fluoroscopic and computationally derived) as a method for ensuring proper hardware placement
- The development of osteobiological adjuvants, which allowed for higher arthrodesis rates and reduced the need for iliac crest bone harvesting
- The adaptation of percutaneous, wire-based, and extension/post-based methods for controlling implants without direct handling of the screws/rods/plates being used
- The discovery of additional access corridors and safe routes to the spinal column

Percutaneous Pedicle Screws and 3D Fixation Methods

In 1982, Magerl described the percutaneous screw placement technique for fracture fixation, but that method involved a connecting rod superficial to the fascia that was typically later removed.[35] Soon afterward, some surgeons began implanting standard pedicle screws, using either larger tubular retractors or the Wiltse plane. Thus, the technique was not percutaneous but did reduce soft-tissue trauma. The earliest commercially successful percutaneous screw system was designed to overcome the perceived problem of screw-to-rod connection. The Sextant system (Medtronic Sofamor Danek) used an arc-shaped rod to have a predefined rod passage trajectory.[16] However, the system was limited to short-segment constructs. Subsequent systems have been developed by nearly every implant manufacturer, and current systems are largely based upon the following: 1) targeting pedicles with fluoroscopy, navigation, or robotics; 2) placement of a Jamshidi needle, followed by exchange for a K-wire; 3) using the Seldinger technique to pass instruments and then a cannulated pedicle screw with extension post over this wire; and 4) rod passage and connection is then achieved freehand using these extension posts to assist in rod insertion.

It is abundantly clear that current methods have been successful from the perspective of widespread adoption. However, numerous opportunities exist for improving screw placement accuracy, improving workflow, and assisting long-segment construct assembly.

Alternative Segmental Fixation Methods

An exhaustive discussion of vertebral fixation methods in MISS is outside the scope of this publication. However, it bears mentioning that while placement of pedicle screw/rod constructs is the most commonly employed MISS fixation technique, other methods are in use and offer unique advantages. A preliminary list would include:

- Cortical screws (while not percutaneous, they require only midline exposure for placement)[48]
- Percutaneous iliac screws[64]
- Facet interference and transfacet screws
- Anterior thoracolumbar plating
- Interspinous fixation devices

Thoracolumbar Interbody Fusion

The history of MISS is almost synonymous in some minds with interbody fusion. Disc removal followed by interbody cage placement is associated with a high rate of arthrodesis. It also allows for proper load sharing, anterior column reconstruction, indirect decompression, and some degree of intersegmental deformity correction.

Posterior Approaches

In 2002, Khoo and Fessler first described the application of a tubular retractor system, microendoscopic technique, and percutaneous pedicle screw system to perform posterior lumbar interbody fusion minimally invasively in 3 patients.[29] This technique expanded on the tubular lumbar laminectomy technique described earlier to include bilateral facetectomies, disc removal, and interbody graft placement all through a tubular retractor, followed by percutaneous screw placement. Holly et al. and Schwender et al. reported successful outcomes with MIS transforaminal lumbar interbody fusion (MIS-TLIF) through a tubular retractor, obviating the need for bilateral tubular access.[22,51] Over the past decade, MIS-TLIF through a tubular retractor has become the posterior approach workhorse for contemporary minimally invasive spine surgeons. Numerous studies comparing the clinical outcomes of tubular MIS-TLIF versus open TLIF consistently demonstrated superior patient outcomes (less estimated blood loss, shorter length of hospital stay, and faster mobilization and return to work) while maintaining similar complication rates in the hands of experienced minimally invasive spine surgeons.[32,38,72]

Over time, the size of the tubular access port has been modified, with smaller ports being used by more skillful surgeons, but it is not uncommon for the diameter of the MIS-TLIF retractors to be 22 mm or even 26 mm.[22] The tissue dissection is thus still significant. A new and attractive method involves combining transforaminal access through Kambin's triangle and endoscopic visualization. We reported on using an endoscope-assisted TLIF technique through an 8-mm port, resulting in less soft-tissue disruption, earlier discharge, and faster recovery (Fig. 3). The technique does not require endotracheal intubation and is done under conscious sedation.[61,62] Comparing tubular MIS-TLIF and endoscopic TLIF, there was a significant decrease in the operative time (96 vs 129 minutes), estimated blood loss (68 vs 235 ml), and length of hospital stay (1.23 vs 3.9 days), resulting in approximately $3400 in lower costs.[60]

Lateral Approaches

A retroperitoneal transpsoas approach with the patient in the lateral decubitus position is a technique that provides minimally invasive access to the anterior and middle spinal column in the thoracolumbar spine. It allows for multilevel access in the thoracolumbar spine without disruption of posterior paraspinal musculature, and it permits a powerful restoration of coronal and segmental alignment. After Mayer and McAffee et al. initially described this technique, Pimenta (Fig. 2C) et al. expanded and furthered the technique to perform interbody fusion.[36,37,40] The combination of a muscle-splitting technique, tubular retractor, and neuromonitoring with continuous-run electromyography became popularized with the extreme-lateral interbody fusion (XLIF). Like anterior lumbar interbody fusion, the lateral approach allowed for placement of large load-bearing cages, maximizing fusion rates, indirect neural decompression, and deformity correction.

The direct lateral route reduced the rate of vascular and sympathectomy injuries, but lumbar plexus and peripheral nerve traction/injuries became more common. For example, femoral nerve injury rates have been reported to be as high as 4.8% at the L4–5 level.[8,57] The identification of safer working zones in the lateral lumbar spine was sought; however, it is possible that there may not be an absolute safe working zone.[3] Subsequent lateral modifications such as a shallow docking technique or a more anterior pre-psoas approach have thus been advocated, and a family of lateral methods has now been developed. Procedures such as the oblique lateral interbody fusion leverage a more anterior approach, which has the potential to allow access as low as L5–S1, anterior longitudinal ligament release for maximizing lordosis, and avoidance of the lumbosacral plexus.[52]

Minimally Invasive Deformity Correction

Open thoracolumbar deformity surgery in adults is associated with major complications rates of 28%–86%.[6,66,71] One of the hopes of MISS is that applying the tissue-sparing principles and techniques could reduce this morbidity rate. Initial forays into MIS deformity correction largely rested on the lateral approach, and it was found that the transpsoas discectomy allowed for bilateral annular release and that this was highly effective for correcting regional coronal deformities.[2,24] More recent techniques have allowed for selective sectioning of the anterior longitudinal ligament and the implantation of hyperlordotic cages to increase in segmental lordosis.[4,11,66] Reports of 15°–30° of added lordosis per disc level have been typical. The results thus appear to approximate the degree of regional lordosis that can be added with anterior lumbar interbody fusion.

Posterior MISS for deformity correction has also been reported. We described both multilevel MIS-TLIF and mini-open pedicle subtraction osteotomy techniques for

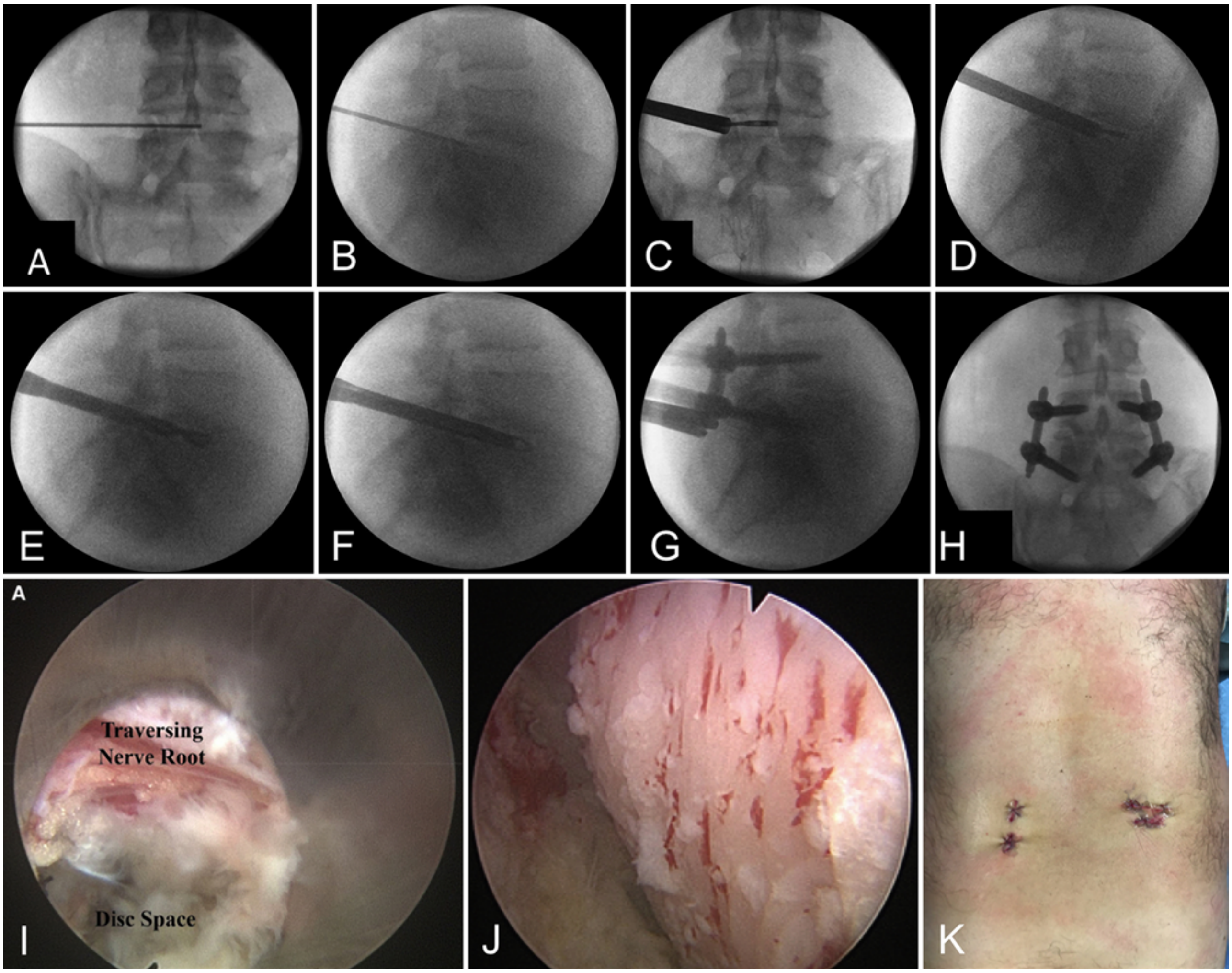

FIG. 3. Awake endoscopic TLIF technique. **A and B:** The intervertebral disc space is accessed via a transforaminal route, as described by Kambin, using a spinal needle. **C and D:** Through an 8-mm endoscopic working cannula, various endoscopic discectomy tools are used to perform a complete discectomy. **E and F:** A combination of bipolar electrocautery, pituitary rongeurs, curettes, and stainless steel brushes are used to prepare the disc space for fusion. **G and H:** The technique relies on indirect decompression of neural elements with the use of an expandable cage (22- or 25-mm OptiMesh Spineology cage). After interbody fusion is completed, percutaneous pedicle screw placement is performed under local anesthesia with liposomal bupivacaine. **I:** Endoscopic view of the traversing nerve root and the disc space. **J:** After the disc and cartilage are removed, the vertebral endplate is prepared for fusion. There is bleeding bone, but cortical bone is still intact. **K:** The entire procedure can be performed through 4 stab incisions (< 1 inch), and they are closed with 3-0 Monocryl and cyanoacrylate tissue adhesive. Panels I and J were reproduced from Wang MY, Grossman J: Endoscopic minimally invasive transforaminal interbody fusion without general anesthesia: initial clinical experience with 1-year follow-up. *Neurosurg Focus 40(2):*E13, 2016. Panel I has been annotated. Copyright American Association of Neurological Surgeons. Published with permission. Figure is available in color online only.

adult deformities. The MIS-TLIF approach can achieve modest deformity corrections of up to 40° of scoliosis and 25° of added lordosis.[58] The mini-open pedicle subtraction osteotomy technique is more powerful and uses a 4-rod technique with in situ assembly and rod/cantilever technique (Fig. 4).[13,59,65] An initial clinical case series found a mean sagittal vertical axis reduction of 60 ± 44.6 mm along with improvement in quality of life and mean reduction of 36 points on the Oswestry Disability Index.

Navigation and Robotics

Three-dimensional surgical navigation for spine surgery was first reported in 1995.[39] Over the past 3 decades, the development and widespread adoption of surgical navigation in spine surgery has found special relevance in MISS, where direct anatomical visualization is limited. Tehli et al. have demonstrated 98% accuracy in pedicle screw placement using 3D navigation and intraoperative image acquisition using the O-arm (Medtronic).[56] Using a CT-guided navigation technique, Smith et al. placed 238 percutaneous pedicle screws at 98% accuracy rate without the use of a Jamshidi needle and K-wire.[54]

There has also been increasing interest in enhancing surgical visualization using adapted head-up displays. In 2015, the launch of Google Glass (Google) garnered a

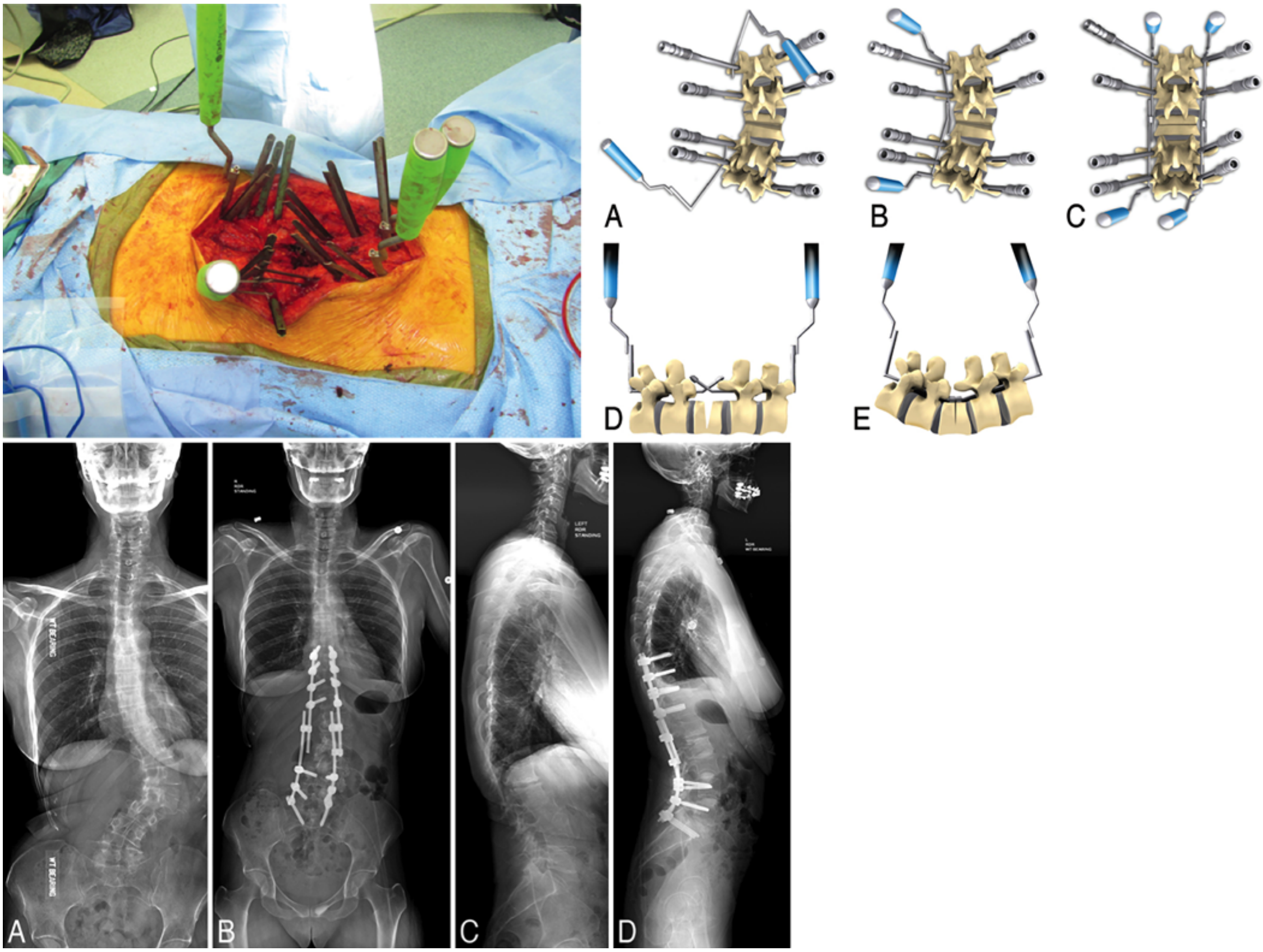

FIG. 4. Minimally invasive deformity correction with mini-open pedicle subtraction osteotomy followed by percutaneous pedicle screw fixation and placement of a 4-rod construct to reduce and close the osteotomy site. **Upper Right:** Panel reproduced from Wang MY, Bordon G: Mini-open pedicle subtraction osteotomy as a treatment for severe adult spinal deformities: case series with initial clinical and radiographic outcomes. *J Neurosurg Spine 24*:769–776, 2016. Copyright Roberto Suazo. Published with permission. Figure is available in color online only.

greater interest for adopting its use in the operating room. Software modifications to Google Glass allowed Chimenti and Mitten[10] to view fluoroscopic images during percutaneous pinning of a hand fracture, and they concluded that Google Glass allowed surgeons to direct their attention toward the operative field more consistently. Yoon et al.[74] performed 3D image-guided pedicle screw placement in 10 patients by transferring image guidance images from a Medtronic Stealth S7 system (Medtronic) obtained with an O-arm system to a Google Glass head-up display screen using an image-transfer device.[34,75]

A marriage of image guidance with effector arm technology has led to the recent application of robots in spinal surgery.[12,55] Systems such as Spine Assist, Renaissance, and Mazor X (Mazor Robotics) now have a track record of assisting surgeons with accurate screw placement (Fig. 5). Other robotic systems have also become available commercially,[9] and it is likely that we will see a proliferation of new robotic and robot-like devices to assist surgeons with various functions in the operating room. The relevance to MISS is 1) the reduction in radiation exposure to the surgeon and patient; 2) accurate and improved percutaneous screw placement;[23,30,44] and 3) assistance with 3D planning and understanding

While the use of robots has heretofore been largely limited to assistance with pedicle screw placement, it may soon be possible to perform more complex surgical tasks such as neural decompression, automated discectomy, and cage placement.[34]

The Health Systems Perspective

The last 75 years have seen major advances in spinal surgery, and this has led to greater consumption of spinal surgery as a service. MISS has been integral in driving many of these changes. Thus, spinal surgeons, policymakers, insurance companies, and patients themselves all have a keen interest in MISS. The ongoing interest in cost, qual-

TABLE 1. Reduction in length of stay and overall healthcare cost for MISS compared with open spine surgery

		Length of Stay (days)		Cost	
Authors & Year	Technique	MISS	Open	MISS	Open
Wang et al., 2012	TLIF	1-level: 3.35; 2-level: 3.4	1-level: 3.6; 2-level: 4.03	1-level: $29,187; 2-level: $33,879	1-level: $29,947; 2-level: $35,984
Cahill et al., 2013	Microdiscectomy	0.9	1.5	$22,358	$27,811
Parker et al., 2014	TLIF	3	4	$38,563	$47,858
Singh et al., 2014	TLIF	2.3	2.9	$19,512	$23,550

ity, and utilization has had an impact, and these areas have been impacted by MISS. MISS has led to greater consumer acceptance of surgery as an option, and the demonstrated advantages of MISS in vulnerable populations such as elderly and obese patients mean that more surgery can be done to help these populations. While this increases overall consumption and cost, MISS also reduces the cost of the surgical intervention (Table 1).[7,41,53,63] Faster recovery, reduction in length of stay, and more rapid mobilization and return to work all play a role in these savings.

Conclusions

The past 75 years have seen tremendous innovation and improvements in spinal surgery. The principle of minimizing soft-tissue disruption while maximizing the goal of surgery remains a core surgical tenet. It is likely that these trends will continue as neurosurgeons seek to improve the care they provide for an ever-growing and aging population that is beginning to demand healthcare as a right.

FIG. 5. The Renaissance Guidance System (Mazor Robotics) is a robotic arm with a rigid tubular portal that aligns itself with preplanned screw trajectory and is locked in place, through which the surgeon can drill and place screws (source: http://cdn.nocamels.com/wp-content/uploads/2017/04/Mazor-Robotics-Renaissance-Guidance-System-for-Spine-Surgery.jpg). Copyright Mazor Robotics. Published with permission. Figure is available in color online only.

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Disclosures

Dr. Yoon reports ownership in MedCyclops, LLC. Dr. Wang reports being a consultant for DePuy Synthes, K2M, and Spineology. He is a patent holder with DePuy Synthes and is a stockholder in Medical Device Partners and ISD.

Author Contributions

Conception and design: both authors. Acquisition of data: Wang. Analysis and interpretation of data: both authors. Drafting the article: both authors. Critically revising the article: both authors. Reviewed submitted version of manuscript: both authors. Approved the final version of the manuscript on behalf of both authors: Wang. Administrative/technical/material support: Wang. Study supervision: Wang.

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