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 inasmuch 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 Williams68 was the precursor to the modern microdiscectomy in use today. Reducing soft-tissue dissection resulted in less postoperative back pain for patients; using the
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. 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. 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. 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,
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.44

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 specimens19 and subsequently in clinical settings in 2002.15 They con-
cluded 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 on 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 ac-

Endoscopic Techniques

Coincident with the proliferation of tubular techniques,
other surgeons advanced and refined working-channel en-
doscopic surgery. Improvements in glass-rod endoscope
technology, digital image processing, and high-definition
video all helped fuel these advancements. The obvious ad-

various subtle but important modifications to the trans-
foraminal access corridor were developed, but limitations
to central canal access persisted. Thus, the interlaminar
route was developed.5 The interlaminar approach allowed
for para-central and central (midline) lumbar discectomy,
and the technique now has been modified to allow for
lumbar stenosis decompression with partial facetectomy
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 forami-
nal pathology (Fig. 2).25,46,47,73

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. Micheile 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 prepara-
tion of bone grafting recipient site. Several major develop-
ments (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 pos-
terolateral) 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 fluoro-
scopically 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 exten-
sion/post-based methods for controlling implants with-
out 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.33 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 percutane-
ous 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.15 However, the
system was limited to short-segment constructs. Subse-
quent systems have been developed by nearly every im-
plant 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 ped-
icle 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)
- **Percutaneous iliac screws**
- **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. 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.

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.

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. The tissue dissection is thus still significant. A new and attractive method involves combining transforminal 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.

The technique does not require endotracheal intubation and is done under conscious sedation. 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.

### 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 paraspinous musculature, and it permits a powerful restoration of coronal and segmental alignment. After Mayer and McAfee et al. initially described this technique, Pimenta (Fig. 2C) et al. expanded and furthered the technique to perform interbody fusion.

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 sympathetic 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. 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. 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.

### Minimally Invasive Deformity Correction

Open thoracolumbar deformity surgery in adults is associated with major complications rates of 28%–86%. One of the hopes of MISS is that applying the tissue-sparing principles and techniques could reduce this morbidity rate. Initial forays into MISS 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. More recent techniques have allowed for selective sectioning of the anterior longitudinal ligament and the implantation of hyperlordotic cages to increase in segmental lordosis. 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...
adult deformities. The MIS-TLIF approach can achieve modest deformity corrections of up to 40° of scoliosis and 25° of added lordosis. 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). 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. 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). 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.

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
greater interest for adopting its use in the operating room. Software modifications to Google Glass allowed Chimenti and Mitten\textsuperscript{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.\textsuperscript{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.\textsuperscript{34,75}

A marriage of image guidance with effector arm technology has led to the recent application of robots in spinal surgery.\textsuperscript{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,\textsuperscript{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;\textsuperscript{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.\textsuperscript{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-

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.
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). 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.

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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. Approved the final version of the manuscript on behalf of both authors. Wang. Data collection: both authors. Administrative/technical/material support: Wang. Study supervision: Wang.

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