Review Article

Current state of minimally invasive spine surgery

Avani S. Vaishnav[1], Yahya A. Othman[1,2], Sohrab S. Virk[1], Catherine Himo Gang[1], Sheeraz A. Qureshi[1,3]

[1]Hospital for Special Surgery, New York, NY, USA; [2]Weill Cornell Medicine-Qatar, Doha, Qatar; [3]Weill Cornell Medical College, New York, NY, USA

Contributions: (I) Conception and design: All authors; (II) Administrative support: All authors; (III) Provision of study materials or patients: All authors; (IV) Collection and assembly of data: All authors; (V) Data analysis and interpretation: All authors; (VI) Manuscript writing: All authors; (VII) Final approval of manuscript: All authors.

Correspondence to: Sheeraz A. Qureshi, MD, MBA. 535 E. 70th St., New York, NY 10017, USA. Email: sheerazqureshimd@HSS.EDU.

Abstract: Over the past two decades, minimally invasive surgical approaches have become increasingly feasible, efficient and popular for the management of a wide range of spinal disorders, with a growing body of research demonstrating numerous advantages of these techniques over the traditional open approach. In this article, we review the technologies and innovations that are expanding the horizon of minimally invasive spine surgery (MISS), and highlight high-quality peer-reviewed literature in the past year that expands our knowledge and understanding of indications, advantages and limitations of MISS.

Keywords: Minimally invasive; spine; navigation; fluoroscopy; robotics; outcomes

Submitted Mar 20, 2019. Accepted for publication Mar 20, 2019.
doi: 10.21037/jss.2019.05.02
View this article at: http://dx.doi.org/10.21037/jss.2019.05.02

Technologies

Navigation

Newer navigation protocols that rely on intraoperative CT registration have improved the accuracy of imaging models and allowed surgeons to rely less on fluoroscopy. Despite concerns regarding ionizing radiation exposure to the patient, use of CT navigation systems was found to reduce radiation exposure by more than 90% compared to traditional fluoroscopic guided percutaneous surgical techniques (1). Furthermore, the surgeon's exposure to radiation is almost eliminated, as the surgeon does not need to be close to the patient during the CT image registration.

The accuracy of navigation has also undergone a huge amount of progress. In addition to higher quality registration, the use of stereotactic 3D cameras allows the system to predict relative position between instruments and anatomical landmarks in real time with higher reliability (2). Amiot *et al.* and Yu *et al.* (3,4). both demonstrated that freehand pedicle screw (PS) placement had a higher rate of error and reoperation compared to navigation assisted placement. The same results were reflected in a meta-analysis of 12 studies conducted by Shin *et al.* (5) However, many other meta-analyses in the literature have failed to demonstrate superiority of computer assisted navigation to free hand PS instrumentation perhaps due to the heterogeneity of studies included. The accuracy of navigation has also undergone a lot of progress. In additional to higher quality registration, the use of stereotactic 3D cameras allows the system to predict relative position between instruments and anatomical landmarks in real time with higher reliability (2). Amiot *et al.* and Yu *et al.* (3,4) both demonstrated that freehand PS placement had a higher rate of error and reoperation compared to navigation assisted placement. Shin *et al.* completed a meta-analysis of 12 studies which also reflected the same results (5). However, many other meta-analyses in the literature have failed to demonstrate superiority of computer assisted navigation to free hand PS instrumentation perhaps due to the heterogeneity of studies included.

Navigation systems rely on the use of reference trackers to keep the registration image in sync throughout the operation regardless of the positioning of the patient. Multiple modalities of anatomic tracking are in use. Pin trackers that are inserted into bony landmarks allow for accurate mapping with relatively few trackers, however

care needs to be taken to ensure that they are kept in place throughout the entire procedure. This can be a challenge since the pins stick out into the surgical field and can be bulky (6). On the other hand (6), on-skin strip trackers have a flat profile and surround the outside of the surgical field instead, offering surgeons less obstruction while maintaining accurate mapping. Overall, navigation technology is trending towards less obstructive tools that fit into the flow of the operative room and are easy to adapt to for the surgeons.

The cost of navigation systems remains one of its prohibitive factors. However, the increased accuracy, the reduced cost of reoperations and management, and the reduced radiation exposure are all factors that can balance out the increased upfront cost (2). The cost of navigation systems remains one of its prohibitive factors. However, the increased accuracy, reduced number and cost of reoperations and management, and reduced radiation exposure are all factors that can balance out the increased upfront cost (2).

Robotics

Robotic surgery has the promise of precision, reliability, and efficiency that allows procedures to be performed quickly and without tissue damage. These qualities give robotic surgery the potential to play an important role in spine surgery. Robots also overcome the issue of mental and physical fatigue that surgeons face especially during long spine cases (2). Robotic surgery has the promise of precision, reliability, efficiency and agility that allows procedures to be performed quickly and without tissue damage. These qualities give robotic surgery the potential to play an important role in spine surgery. Robots also overcome the issue of mental and physical fatigue that surgeons face especially during long spine cases (2).

Robotic surgical devices can work seamlessly with navigation systems and integrate well into minimally invasive spine surgery (MISS). Robotic devices that incorporate computer assisted navigation for the purpose of accurate PS insertion are already in use. These devices are smaller and are usually mounted on anatomic landmarks using K-wires. This helps overcome interference issues with navigation that are faced in non-robotic cases. The accuracy of robotic PS instrumentation is superior fluoroscopy guided counterparts, as reported in multiple studies (7,8). Robotic surgical devices can work seamlessly with navigation systems and integrate well into MISS. Already in use are robotic devices that incorporate computer assisted navigation for the purpose of accurate PS insertion. These devices are smaller, and usually are mounted on anatomic landmarks using K-wires; this helps overcome interference issues with navigation that are faced in non-robotic cases. The accuracy of robotic PS instrumentation is superior fluoroscopy guided counterparts, as reported in multiple studies (7,8).

However, there doesn't seem to be a lot of literature on robotic device use in spinal surgery outside of screw insertion. The da Vinci surgical system has been used for minimally invasive surgery (MIS) anterior lumbar interbody fusion (ALIF) procedures and is purported to have greater efficacy and safety. Nevertheless, more research is needed for its benefit to be well understood (9).

Unfortunately, the issue of cost still prevails in the realm of robotic spine surgery, as currently the added benefit of robotics is limited, and although accuracy is higher than free hand PS insertion, it is at best equivalent to computer assisted navigation (2).

Arthroscopic/endoscopic spine surgery

Endoscopic spine surgery was first attempted by Kambin *et al.* in 1988 (10). However, it is only recently that the technique has been popularized due to the concurrent advancement in tools and imaging modalities. The use of endoscopic techniques in spine surgery has the same advantages as other forms of MISS. Respecting the surrounding tissue, avoiding blood loss, and achieving desired functional outcomes earlier are factors also seen with endoscopic surgery (11). Endoscopic spine surgery was first attempted by Kambin *et al.* in 1988 (10). However, it is only recently that the technique has been popularized due to the concurrent advancement in tools and imaging modalities. The use of endoscopic techniques in spine surgery has the same desirable factors as other aspects of MISS of respecting the surrounding tissue, avoiding blood loss, and earlier functional outcomes (11).

Endoscopic spinal surgeries are expanding beyond the lumbar region, and now are performed on the cervical as well as thoracic spine. Commonly, endoscopic procedures are carried out for discectomies and decompression.

For lumbar procedures the two surgical approaches that have been well described in the literature and are widely used are transforaminal and intralaminar. These are especially frequently performed in younger patients, as they permit quick return to daily activities. In particular, endoscopic surgery has shown great success in treatment of challenging far lateral lumbar disc herniation using a

transforaminal percutaneous approach (12).

Success rates for endoscopic microdiscectomies have been shown to be equivalent to open microdiscectomies, according to a study that included 10,228 patients (13). Like other minimally invasive techniques, endoscopic spine surgery is also faced with the challenge of surgical technique mastery. However, complications arising from early operations seem to diminish with consecutive cases, they nevertheless are significant enough to consider (14). Success rates for endoscopic microdiscectomies have been shown to be equivalent to open microdiscectomies, according to a study that included 10,228 patients (13). Like other minimally invasive techniques, endoscopic spine surgery is also faced with the challenge of surgical technique mastery. The complications arising from early operations seem to diminish with consecutive cases, however are significant enough to consider (14).

Learning curve and simulation models

Physicians starting MISS face operative challenges in their first cases. Studies have placed that number to be between 32–44 cases (15-17). Although complication rates between MIS and open surgeries are equivalent, surgeons starting to practice using minimally invasive techniques initially face a higher rate of complications that eventually normalizes. This learning curve is attributed to the absence of tactile sensation, the restricted surgical field and the unfamiliarity of the surgeon. Physicians starting MISS face operative challenges in their first 32–44 cases (15-17). Although complication rates between MIS and open surgeries are equivalent, surgeons practicing on minimally invasive techniques face a higher rate of complications that eventually normalizes. This learning curve is attributed to the absence of tactile sensation, the restricted surgical field and the unfamiliarity of the surgeon.

However, overcoming the learning curve is hypothesized to be facilitated with the improvement in intuitive real-time navigation technology, as this allows surgeons to better discern the operative anatomy. In fact, incorporation of 3D guided navigation has shown a reduction in the error rate in early procedures according to a prospective study conducted by Sedlack *et al.* (18). However, overcoming the learning curve is hypothesized to be facilitated with the improvement in intuitive real-time navigation technology, as this allows surgeons to better discern the operative anatomy. Incorporation of 3D guided navigation surgery showed reduce the error rate in early procedures according to a prospective study conducted by Sedlack *et al.* (18).

That being said, current advice remains the same: having a complete understanding of the anatomy before starting MIS and beginning with simple cases. In fact, surgeons experience did not correlate with patient outcome for decompression cases according to one study (19). MIS fusions on the other hand have a steeper learning curve. Studies looking at complication rates for fusion procedures have reported a significantly higher number of dural tears, cage migration, and adverse events in early cases (20). The being said current advice remains the same, beginning with simple cases and having a complete understanding of the anatomy. In fact, surgeons experience did not correlate with patient outcome for decompression cases according to one study (19). MIS fusions on the other hand have a steeper learning curve. Studies looking at complication rates for fusion procedures have reported a significantly higher number of dural tears, cage migration, and adverse events (20).

However, there is a lot of focus now on implementing high fidelity training models for spine surgeries, and in particular for MISSs. These simulation modules help facilitate the initial learning period for the novitiate surgeon (21). The use of simulation models has been shown to reduce the error rate in early procedures in a prospective study (18). However, a lot of focus is now on implementing high fidelity training models for spine, and in particular, MISSs. These simulation modules help facilitate the initial learning period for the novitiate surgeon (21). The use of simulation models has been shown to reduce the error rate in early procedures in a prospective study (18).

Cervical spine

Posterior cervical approach

A number of case series and comparative reports have studied the outcomes, techniques and feasibility of MIS posterior approaches to the cervical spine for the management of a wide range of degenerative pathology including cervical spondylotic myelopathy (CSM), disc herniation and stenosis. These studies have reported good clinical results, improvement of symptoms and a favorable complication profile for minimally invasive (MIS) tubular retractor-assisted approach for posterior cervical laminectomy in patients with CSM (22), percutaneous endoscopic posterior cervical foraminotomy (23,24) and posterior percutaneous endoscopic cervical discectomy (P-PECD) (25,26). These studies have reported low rates of revision, conversion to open surgery

and need for subsequent anterior cervical discectomy and fusion (ACDF) (25), and have found functional outcomes and revision rates to be comparable to those seen with ACDF (27), which is considered the gold-standard in these patient populations.

Despite numerous reports of good clinical outcomes with MIS procedures, a commonly cited deterrent to the adoption of these techniques is the steep learning curve of these procedures. Thus, a valuable addition to the literature in this regard is a prospective study that reports the feasibility and outcomes of a modified technique for P-PECD that can potentially shorten the learning curve (28). This surgical technique involves use of a K-wire anchored to the target point instead of a needle to insert the working sheath, thus facilitating easier identification of the target point under endoscopic view with less need for repeated fluoroscopic confirmation. When compared to conventional PECD, this technique showed significantly shorter operative time and decreased fluoroscopy time, with no difference in clinical outcomes. In addition to improvements in surgical techniques, few studies have also reported on the feasibility and outcomes of using different anesthetic techniques for these procedures. One such study that describes the technique for P-PECD performed via full endoscopic approach under local anesthesia for soft disc herniation causing radicular symptoms reported clinical success in over 95% of patients, no intra- or post-operative complications and no deterioration of existing symptoms.

Future studies focusing on techniques to shorten the learning curve, improvement in anesthetic and surgical techniques, and long-term outcomes will facilitate wider adoption of these procedures.

Anterior cervical approach

MIS anterior approach to the cervical spine most commonly reported in the recent literature is an anterior PECD (A-PECD). A retrospective case series of over 200 patients who underwent A-PECD for cervical myelopathy or unilateral radiculopathy (29) describes significant clinical improvement and a low rate of operative complications, but reported a loss of disc height in all patients. While the authors report that the loss of disc height was asymptomatic, long-term implications of iatrogenic disc damage and loss of disc height are unknown. To mitigate this concern, a few reports have described a transcorporeal A-PECD approach for cervical disc herniations that have migrated upward or downward dorsal to the vertebral body and cannot be easily managed by a posterior approach or an ACDF. One such study (30) reports good clinical outcomes and healing of the osseous tunnel by 6 months, with the additional benefits of being able to adjust the trajectory of the transcorporeal tunnel depending target location and preventing damage to the intervertebral disc. Further study on techniques and outcomes of this procedure are needed to establish its efficacy and results with greater confidence.

Thoracic spine

Minimally invasive thoracic discectomy

Although MIS approaches to the thoracic spine are often challenging due to limited space and presence of vital structures in close proximity, MIS (31) and endoscopic techniques (32) have been described for thoracic disc herniations. A retrospective case series, which studied the feasibility and benefits of adding stereotactic navigation to MIS thoracic discectomy concluded that the use of navigation provides better visualization central and paracentral disc herniation and can thus expand the indications of this procedure (31). Another retrospective study describing the technical feasibility and outcomes of full-endoscopic decompression for thoracic disc herniation and stenosis demonstrated that a full-endoscopic approach can provide access to various target areas by using different approaches (interlaminar, extraforaminal or transthoracic retropleural) and results in sufficient decompression, with a reduction in operative time compared to conventional procedures and minimal blood loss. Incorporation of newer technologies such as navigation and endoscopy that facilitate better visualization may improve safety and outcomes, and increase surgeon-comfort with these techniques.

Lumbo-sacral spine

Endoscopic decompression procedures

Endoscopic approaches have been described for the management of disc herniation as well as bony stenosis, with various surgical techniques being adopted depending on the underlying pathology. Retrospective studies (13,33,34) comparing percutaneous endoscopic lumbar discectomy (PELD) to other endoscopic techniques (microendoscopic discectomy and unilateral biportal endoscopic discectomy) and to conventional microdiscectomy report that PELD is less invasive and results in lower peri-operative morbidity, less iatrogenic muscle injury, lower post-operative pain,

shorter hospital stays and better long-term functional outcomes compared to other endoscopic or conventional microsurgical procedures. PELD can be performed via a transforaminal (PELD-T) or interlaminar (PELD-I) approach, with a recent meta-analysis (35) reporting equivalent clinical and functional outcomes between the two approaches. Although there was no difference in overall complication rates, the interlaminar approach resulted in a greater incidence of dural tears. Thus, PELD particularly when performed via a transforaminal approach seems to be a safe, feasible and effective MIS technique for the management of disc herniations.

Endoscopic decompression surgery has also demonstrated encouraging clinical outcomes for degenerative stenosis (36) and has been shown to be feasible under local anaesthesia (37). A multi-institutional study of 533 patients that focused on intra- and peri-operative complications associated with endoscopic spine surgery reported a favorable complications profile, with only 0.54% and 0.36% of cases resulting in durotomies and epidural hematomas respectively, and only 4 patients experiencing recurrent herniation within 3 months of the index operation.

Lateral approaches for interbody fusion

Lateral lumbar interbody fusion (LLIF), which comprises the oblique approach, i.e., oblique lumbar interbody fusion (OLIF) and the lateral transpsoas approach, i.e., direct lateral interbody fusion (DLIF), confers the ability to place a large interbody cage via a minimally invasive approach and hence has gained popularity in the management of degenerative and deformity conditions of the spine. Studies comparing LLIF to minimally invasive transforaminal lumbar interbody fusion (MI-TLIF) (38,39) have reported equivalent clinical and radiographic outcomes, with additional benefits of greater restoration of disc height, shorter operative times and quicker return to work seen with the lateral approach. LLIF has also been shown to be feasible and effective approach for the management of adult spinal deformity (40) and adjacent segment degeneration (41), and in elderly patients (42). Furthermore, authors have reported on feasibility and peri-operative outcomes of single-position DLIF and OLIF with bilateral PS fixation (43), which could potentially improve operative efficiency and cost-savings by reducing the time and staffing associated with patient-repositioning for posterior fixation.

However, complications such as inadequate decompression, graft subsidence and post-operative neurologic deficits have been reported, with a study that used intra-operative CT myelograms to assess the adequacy of indirect neural decompression with LLIF reporting that in about 1/5th of levels operated, adequate decompression was not achieved (44). This underscores the need for appropriate patient selection for these procedures. A study evaluating the utility of intra-operative neuromonitoring in DLIF procedures (45) found that compared to electromyography (EMG) alone, the use of motor evoked potential (MEP) monitoring resulted in lower a rate of immediate post-operative neurologic deficits, both sensory and motor, and a lower rate of unresolved deficits in the long-term, thus suggesting that it may be valuable to perform MEP monitoring as routine practice during LLIF procedures.

Outcomes of MISS in obese patients

Historically, obesity has been associated with increased morbidity following surgical procedures. However, MIS procedures that results in less iatrogenic injury can potentially decrease this morbidity, as demonstrated by studies that have found MI-TLIF to be superior to open TLIF in obese patients (46). Furthermore, previous studies (47-49) have reported that obesity is not a risk factor for revision surgery or post-operative complications following MI-TLIF. However, a few studies have reported greater peri-operative morbidity in obese patients, with a greater incidence of post-operative hematoma (48), and longer operative time and length of stay (49). The literature is unclear regarding functional outcomes, with one systematic review (49) demonstrating equivalent functional outcomes between obese and non-obese patients undergoing both, decompression and fusion surgeries, but another retrospective study (50) reporting a lower magnitude and rate of clinical improvement in obese patients. These findings suggest that although a MIS approach results in a more favorable outcomes and complications profile compared to an open approach in obese patients, the rate of complications is higher and magnitude of clinical improvement is lower than that seen in non-obese patients undergoing the same MIS procedure.

MISS techniques for revision surgery

In a retrospective series of 43 patients (51) who underwent revision MIS tubular discectomy reported good clinical outcomes and no complications, thus suggesting that this approach provides the advantage of avoiding scar tissue

dissection that may be encountered during traditional open revision surgeries. Another retrospective study which evaluated the outcomes of revision decompression accompanied by a primary fusion also found that the revision procedure does not compromise clinical outcomes, with this procedure showing equivalent clinical outcomes to a primary fusion (52).

PS fixation

PS fixation is commonly used for stabilization of the spine and to provide supplemental posterior fixation. The trend towards minimally invasive surgical procedures and advancements in intra-operative imaging and navigation have led to an increasing number of PS placements being performed using MIS techniques. Numerous studies (53,54) have reported benefits of real-time image guidance and 3D navigation compared to conventional 2D fluoroscopy for PS placements, which include greater accuracy of screw placement and a significant reduction in radiation exposure to patients and the surgeon and operating room (OR) staff, without an increase in operative time or complication rates. Navigation also provides the capability of intra-operatively confirming appropriate screw positioning, thus allowing for intra-operative revision of malpositioned screws and consequently minimizing the need for revision surgeries.

Metabolic bone disease and spine tumors

A meta-analysis (55) comparing MIS and open approaches for the management of metastatic spinal disease reported equivalent functional outcomes and post-operative pain in the two groups, with reduced morbidity and length of stay with MIS procedures. Barzilai *et al.* (56) present an MIS treatment algorithm for the management of spinal metastasis based on the underlying pathology. In their experience, this minimal access algorithm led to significant improvement in patient reported outcomes, particularly in terms of pain, activity, ability to work and enjoyment of life, and could also facilitate an early return to systemic and radiation therapy.

Deformity

Miladi *et al.* presented a series of 100 consecutive young patients with neuromuscular scoliosis all treated with minimally invasive fusionless surgery (57). They were able to demonstrate significant correction of Cobb's angle and pelvic obliquity that was maintained at prolonged follow up (2–9 years). Additionally, this fusionless approach encountered fewer complications compared to arthrodesis surgery. Park *et al.* (40) investigated the impact of performing MIS-LLIF in addition to posterior spinal fusion surgery performed 5–11 days later compared to just posterior spinal fusion for adult spinal deformities and found a significantly higher sagittal Cobb's angle correction in the combined group compared to the single surgery group. The use of MIS for managing deformity is increasing, as are the indications. We are seeing that populations traditionally managed using an open approach are achieving equivalent outcomes using MIS. Furthermore, MIS for deformity cases tend to experience fewer complications.

Conclusions

In recent years there has been a shift towards minimally invasive surgical techniques, which has been heralded by significant advancements in imaging and navigation technologies, refinement of operative techniques, availability of biologics and customizable implants, and most importantly, evidence of feasibility, efficacy, safety and value compared to traditional approaches as demonstrated by the current literature. The increasing adoption of MISS techniques and widespread interest in outcomes of these procedures is evidenced by the large and constantly growing body of literature on this topic. Although MIS techniques have historically been most commonly utilized for degenerative spinal conditions, advancements of these techniques and increased surgeon comfort with MISS procedures have allowed for the expansion of indications to populations such deformity surgeries and in obese patients, in which the implementation of MISS techniques has been thought to be particularly challenging. In light of the current trend of increased interest in and adoption of MISS approaches, we anticipate continued innovation of new technologies, development and refinement of surgical techniques based on patient outcomes, expansion of indications of MISS, and increased accessibility of these procedures to a broader patient population.

Acknowledgments

None.

Footnote

Conflicts of Interest: Dr. SA Qureshi: Currently receiving

Consulting Fees from Zimmer-Biomet, Stryker Spine, Globus Medical, Inc., K2M, OnPoint Surgical, Inc., Paradigm Spine; Shareholder Interest in Avaz Surgical, Vital 5; and Royalties from RTI, Zimmer-Biomet, Stryker Spine; Board membership at Healthgrades, Minimally Invasive Spine Study Group. The other authors have no conflicts of interest to declare.

References

1. Kraus MD, Krischak G, Keppler P, et al. Can Computer-assisted Surgery Reduce the Effective Dose for Spinal Fusion and Sacroiliac Screw Insertion? Clin Orthop Relat Res 2010;468:2419-29.
2. Overley SC, Cho SK, Mehta AI, et al. Navigation and Robotics in Spinal Surgery: Where Are We Now? Neurosurgery 2017;80:S86-S99.
3. Amiot LP, Lang K, Putzier M, et al. Comparative results between conventional and computer-assisted pedicle screw installation in the thoracic, lumbar, and sacral spine. Spine (Phila Pa 1976) 2000;25:606-14.
4. Yu X, Xu L, Bi L. Spinal navigation with intra-operative 3D-imaging modality in lumbar pedicle screw fixation. Zhonghua Yi Xue Za Zhi 2008;88:1905-8.
5. Shin BJ, James AR, Njoku IU, et al. Pedicle screw navigation: a systematic review and meta-analysis of perforation risk for computer-navigated versus freehand insertion. J Neurosurg Spine 2012;17:113-22.
6. Lonjon N, Chan-Seng E, Costalat V, et al. Robot-assisted spine surgery: feasibility study through a prospective case-matched analysis. Eur Spine J 2016;25:947-55.
7. Roser F, Tatagiba M, Maier G. Spinal robotics: current applications and future perspectives. Neurosurgery 2013;72 Suppl 1:12-8.
8. Schizas C, Thein E, Kwiatkowski B, et al. Pedicle screw insertion: robotic assistance versus conventional C-arm fluoroscopy. Acta Orthop Belg 2012;78:240-5.
9. Lee Z, Lee JY, Welch WC, et al. Technique and surgical outcomes of robot-assisted anterior lumbar interbody fusion. J Robot Surg 2013;7:177-85.
10. Kambin P, Nixon JE, Chait A, et al. Annular protrusion: pathophysiology and roentgenographic appearance. Spine (Phila Pa 1976) 1988;13:671-5.
11. Telfeian AE, Iprenburg M, Wagner R. Endoscopic Spine Surgery: Distance Patients Will Travel for Minimally Invasive Spine Surgery. Pain Physician 2017;20:E145-9.
12. Lew SM, Mehalic TF, Fagone KL. Transforaminal percutaneous endoscopic discectomy in the treatment of far-lateral and foraminal lumbar disc herniations. J Neurosurg 2001;94:216-20.
13. Choi KC, Shim HK, Hwang JS, et al. Comparison of Surgical Invasiveness Between Microdiscectomy and 3 Different Endoscopic Discectomy Techniques for Lumbar Disc Herniation. World Neurosurg 2018;116:e750-8.
14. Wang XS, Sun RF, Ji Q, et al. A meta-analysis of interlaminar minimally invasive discectomy compared to conventional microdiscectomy for lumbar disk herniation. Clin Neurol Neurosurg 2014;127:149-57.
15. Epstein NE. Learning curves for minimally invasive spine surgeries: Are they worth it? Surg Neurol Int 2017;8:61.
16. Sharif S, Afsar A. Learning Curve and Minimally Invasive Spine Surgery. World Neurosurg 2018;119:472-8.
17. Sclafani JA, Kim CW. Complications associated with the initial learning curve of minimally invasive spine surgery: A systematic review. Clin Orthop Relat Res 2014;472:1711-7.
18. Sedlack RE, Kolars JC. Computer simulator training enhances the competency of gastroenterology fellows at colonoscopy: results of a pilot study. Am J Gastroenterol 2004;99:33-7.
19. Ahn J, Iqbal A, Manning BT, et al. Minimally invasive lumbar decompression—the surgical learning curve. Spine J 2016;16:909-16.
20. Nandyala SV, Fineberg SJ, Pelton M, et al. Minimally invasive transforaminal lumbar interbody fusion: one surgeon's learning curve. Spine J 2014;14:1460-5.
21. Chitale R, Ghobrial GM, Lobel D, et al. Simulated lumbar minimally invasive surgery educational model with didactic and technical components. Neurosurgery 2013;73 Suppl 1:107-10.
22. Ross MN, Ross DA. Minimally invasive cervical laminectomy for cervical spondylotic myelopathy. Clin Spine Surg 2018;31:331-8.
23. Lee U, Kim CH, Chung CK, et al. The Recovery of Motor Strength after Posterior Percutaneous Endoscopic Cervical Foraminotomy and Discectomy. World Neurosurg 2018;115:e532-8.
24. Wu PF, Liu BH, Wang B, et al. Complications of Full-Endoscopic Versus Microendoscopic Foraminotomy for Cervical Radiculopathy: A Systematic Review and Meta-Analysis. World Neurosurg 2018;114:217-27.
25. Zheng C, Huang X, Yu J, et al. Posterior Percutaneous Endoscopic Cervical Diskectomy: A Single-Center Experience of 252 Cases. World Neurosurg 2018;120:e63-7.
26. Wan Q, Zhang D, Li S, et al. Posterior percutaneous

full-endoscopic cervical discectomy under local anesthesia for cervical radiculopathy due to soft-disc herniation: a preliminary clinical study. J Neurosurg Spine 2018;29:351-7.
27. Malham GM, Parker RM. Early experience of placing image-guided minimally invasive pedicle screws without K-wires or bone-anchored trackers. J Neurosurg Spine 2018;28:357-63.
28. Liao C, Ren Q, Chu L, et al. Modified posterior percutaneous endoscopic cervical discectomy for lateral cervical disc herniation: the vertical anchoring technique. Eur Spine J 2018;27:1460-8.
29. Parihar VS, Yadav N, Ratre S, et al. Endoscopic Anterior Approach for Cervical Disc Disease (Disc Preserving Surgery). World Neurosurg 2018;115:e599-609.
30. Chu L, Yang JS, Yu KX, et al. Usage of Bone Wax to Facilitate Percutaneous Endoscopic Cervical Discectomy Via Anterior Transcorporeal Approach for Cervical Intervertebral Disc Herniation. World Neurosurg 2018;118:102-8.
31. Nakhla J, Bhashyam N, De la Garza Ramos R, et al. Minimally invasive transpedicular approach for the treatment of central calcified thoracic disc disease: a technical note. Eur Spine J 2018;27:1575-85.
32. Ruetten S, Hahn P, Oezdemir S, et al. Full-endoscopic uniportal decompression in disc herniations and stenosis of the thoracic spine using the interlaminar, extraforaminal, or transthoracic retropleural approach. J Neurosurg Spine 2018;29:157-68.
33. Liu X, Yuan S, Tian Y, et al. Comparison of percutaneous endoscopic transforaminal discectomy, microendoscopic discectomy, and microdiscectomy for symptomatic lumbar disc herniation: minimum 2-year follow-up results. J Neurosurg Spine 2018;28:317-25.
34. Li H, Jiang C, Mu X, et al. Comparison of MED and PELD in the Treatment of Adolescent Lumbar Disc Herniation: A 5-Year Retrospective Follow-Up. World Neurosurg 2018;112:e255-60.
35. Chen J, Jing X, Li C, et al. Percutaneous Endoscopic Lumbar Discectomy for L5S1 Lumbar Disc Herniation Using a Transforaminal Approach Versus an Interlaminar Approach: A Systematic Review and Meta-Analysis. World Neurosurg 2018;116:412-420.e2.
36. Heo DH, Quillo-Olvera J, Park CK. Can Percutaneous Biportal Endoscopic Surgery Achieve Enough Canal Decompression for Degenerative Lumbar Stenosis? Prospective Case-Control Study. World Neurosurg 2018;120:e684-9.
37. Youn MS, Shin JK, Goh TS, et al. Endoscopic posterior decompression under local anesthesia for degenerative lumbar spinal stenosis. J Neurosurg Spine 2018;29:661-6.
38. Lin GX, Akbary K, Kotheeranurak V, et al. Clinical and Radiologic Outcomes of Direct Versus Indirect Decompression with Lumbar Interbody Fusion: A Matched-Pair Comparison Analysis. World Neurosurg 2018;119:e898-909.
39. Verla T, Winnegan L, Mayer R, et al. Minimally Invasive Transforaminal Versus Direct Lateral Lumbar Interbody Fusion: Effect on Return to Work, Narcotic Use, and Quality of life. World Neurosurg 2018;116:e321-8.
40. Park HY, Ha KY, Kim YH, et al. Minimally invasive lateral lumbar interbody fusion for adult spinal deformity. Spine (Phila Pa 1976) 2018;43:E813-21.
41. Louie PK, Varthi AG, Narain AS, et al. Stand-alone lateral lumbar interbody fusion for the treatment of symptomatic adjacent segment degeneration following previous lumbar fusion. Spine J 2018;18:2025-32.
42. Agarwal N, Faramand A, Alan N, et al. Lateral lumbar interbody fusion in the elderly: a 10-year experience. J Neurosurg Spine 2018;29:525-9.
43. Blizzard DJ, Thomas JA. MIS Single-position Lateral and Oblique Lateral Lumbar Interbody Fusion and Bilateral Pedicle Screw Fixation. Spine (Phila Pa 1976) 2018;43:440-6.
44. Hayama S, Nakano A, Nakaya Y, et al. The Evaluation of Indirect Neural Decompression After Lateral Lumbar Interbody Fusion Using Intraoperative Computed Tomography Myelogram. World Neurosurg 2018;120:e710-8.
45. Riley MR, Doan AT, Vogel RW, et al. Use of motor evoked potentials during lateral lumbar interbody fusion reduces postoperative deficits. Spine J 2018;18:1763-78.
46. Tan JH, Liu G, Ng R, et al. Is MIS-TLIF superior to open TLIF in obese patients?: A systematic review and meta-analysis. Eur Spine J 2018;27:1877-86.
47. Narain AS, Hijji FY, Bohl DD, et al. Is Body Mass Index a Risk Factor for Revision Procedures after Minimally Invasive Transforaminal Lumbar Interbody Fusion? Clin Spine Surg 2018;31:E85-91.
48. Senker W, Stefanits H, Gmeiner M, et al. Does Obesity Affect Perioperative and Postoperative Morbidity and Complication Rates After Minimal Access Spinal Technologies in Surgery for Lumbar Degenerative Disc Disease. World Neurosurg 2018;111:e374-85.
49. Wang T, Han C, Jiang H, et al. The Effect of Obesity on Clinical Outcomes After Minimally Invasive Surgery of

the Spine: A Systematic Review and Meta-Analysis. World Neurosurg 2018;110:e438-49.
50. Kapetanakis S, Gkantsinikoudis N, Chaniotakis C, et al. Percutaneous Transforaminal Endoscopic Discectomy for the Treatment of Lumbar Disc Herniation in Obese Patients: Health-Related Quality of Life Assessment in a 2-Year Follow-Up. World Neurosurg 2018;113:e638-49.
51. Felbaum DR, Stewart JJ, Distaso C, et al. Complication rate in minimally invasive revision lumbar discectomy. Clin Spine Surg 2018;31:E266-9.
52. Khechen B, Haws BE, Patel DV, et al. Comparison of Postoperative Outcomes between Primary MIS TLIF and MIS TLIF as a Revision Procedure to Primary Decompression. Spine (Phila Pa 1976) 2018. [Epub ahead of print].
53. Tajsic T, Patel K, Farmer R, et al. Spinal navigation for minimally invasive thoracic and lumbosacral spine fixation: implications for radiation exposure, operative time, and accuracy of pedicle screw placement. Eur Spine J 2018;27:1918-24.
54. Fomekong E, Pierrard J, Raftopoulos C. Comparative Cohort Study of Percutaneous Pedicle Screw Implantation without Versus with Navigation in Patients Undergoing Surgery for Degenerative Lumbar Disc Disease. World Neurosurg 2018;111:e410-7.
55. Lu VM, Alvi MA, Goyal A, et al. The Potential of Minimally Invasive Surgery to Treat Metastatic Spinal Disease versus Open Surgery: A Systematic Review and Meta-Analysis. World Neurosurg 2018;112:e859-68.
56. Barzilai O, McLaughlin L, Amato MK, et al. Minimal Access Surgery for Spinal Metastases: Prospective Evaluation of a Treatment Algorithm Using Patient-Reported Outcomes. World Neurosurg 2018;120:e889-901.
57. Miladi L, Gaume M, Khouri N, et al. Minimally Invasive Surgery for Neuromuscular Scoliosis. Spine (Phila Pa 1976) 2018;43:E968-75.

Cite this article as: Vaishnav AS, Othman YA, Virk SS, Gang CH, Qureshi SA. Current state of minimally invasive spine surgery. J Spine Surg 2019;5(Suppl 1):S2-S10. doi: 10.21037/jss.2019.05.02

