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Review Article

The Role and Future of Endoscopic Spine Surgery: A Narrative Review

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Many types of surgeries are changing from conventional to minimally invasive techniques. Techniques in spine surgery have also changed, with endoscopic spine surgery (ESS) becoming a major surgical technique. Although ESS has advantages such as less soft tissue dissection and normal structure damage, reduced blood loss, less epidural scarring, reduced hospital stay, and earlier functional recovery, it is not possible to replace all spine surgery techniques with ESS. ESS was first used for discectomy in the lumbar spine, but the range of ESS has expanded to cover the entire spine, including the cervical and thoracic spine. With improvements in ESS instruments (optics, endoscope, endoscopic drill and shaver, irrigation pump, and multiportal endoscopic), limitations of ESS have gradually decreased, and it is possible to apply ESS to more spine pathologies. ESS currently incorporates new technologies, such as navigation, augmented and virtual reality, robotics, and 3-dimentional and ultraresolution visualization, to innovate and improve outcomes. In this article, we review the history and current status of ESS, and discuss future goals and possibilities for ESS through comparisons with conventional surgical techniques.

Keywords: Endoscopic spine surgery, Minimal invasive surgery, Navigation, Augmented reality, Robot-assisted surgery

INTRODUCTION

As life expectancy increases, spinal diseases are also becoming more frequent[1] and the demand for minimally invasive spine surgery (MISS) and endoscopic spine surgery (ESS) for surgical treatment of spine diseases has increased. Concomitantly, ESS has been recognized as an important technique for spine sugery.[2] Elderly patients with spinal diseases typically have many comorbidities and medical problems, and therefore the surgeon's burden increases. Improvements in ESS instrumentation (optics, endoscopes, endoscopic drills and shavers, irrigation pumps, and multiportal endoscopes) have addressed previous limitations of ESS, making it possible to apply ESS to a wider range of spine pathologies.[3] ESS is now used to treat many degenerative spine diseases, including massive herniated discs and spinal stenosis.[4]

ESS is quickly replacing conventional lumbar spine surgery. Originally used primarily for discectomy, ESS is now used for interbody fusion with additional percutaneous screw fixation.[3,5] Many studies have demonstrated that ESS can be safely applied in cervical and thoracic spine surgery.[6,7] With improvements of the equipment, ESS is overcoming its limitations and becoming applicable not only in degenerative spine disease treatment but also to other pathologies such as tumors, trauma, and deformities.[8,9] The purpose of this article is to review the history of ESS development, verify the current utility of ESS, and suggest directions of future development. In addition, we discuss the future goals and possibilities of ESS through comparisons with conventional surgical techniques.

HISTORY OF ESS

Krause and Oppenheim described the first lumbar discectomy in 1908, but the earliest surgical techniques were accompanied by serious complications such as cerebrospinal fluid leakage and segmental instability, which could lead to postoperative back pain.[10,11] Therefore, many surgeons sought less tissue-damaging approaches. Yasargil[12] and Casper[13] separately introduced microsurgical approaches in lumbar disc surgery in 1977, and this technique has become the gold standard for spine surgery worldwide.

Early attempts to reach the disc space percutaneously started in the 1970s. Kambin and Sampson[14] (1973) and Hijikata[15] (1975) introduced a posterolateral approach for fluoroscopic-guided percutaneous discectomy through a cannula. Kambin and Sampson[14] conducted numerous cadaveric studies and additionally described the safe triangular zone for docking and working on the transforaminal region, allowing a variety of surgical techniques to approach through the safe triangular zone. The first application of a modified arthroscope was announced by Forst and Hausman[16] in 1983. Kambin et al.[17] reported direct visualization using endoscopes in 1988. Schreiber et al.[18] adapted arthroscopic instruments for removal of the nucleus pulposus under direct view in 1989, reporting an overall success rate of 72.5% for sciatica. Ten years later, a prospective randomized study by Hermantin compared video-assisted arthroscopic microdiscectomy to traditional open microdiscectomy and found that patients who underwent endoscopic surgery had higher satisfaction, shorter length of hospital stay, and less narcotic usage postoperatively than those who did not.[4] Classical ESS using a single incision is now classified as "full endoscopic spine surgery" and comprises most ESS.[19]

In the late 1990s, Yeung[20] developed the first fully functional endoscopic system. Using a multichannel endoscope with continuous fluid irrigation, Yeung and colleagues described successful surgical outcomes in cases of disc herniation. Around the same time, Foley developed a tubular retractor and initiated microendoscopic discectomy, which became an important surgical technique in minimally invasive discectomy and fusion (Fig. 1).[21,22]

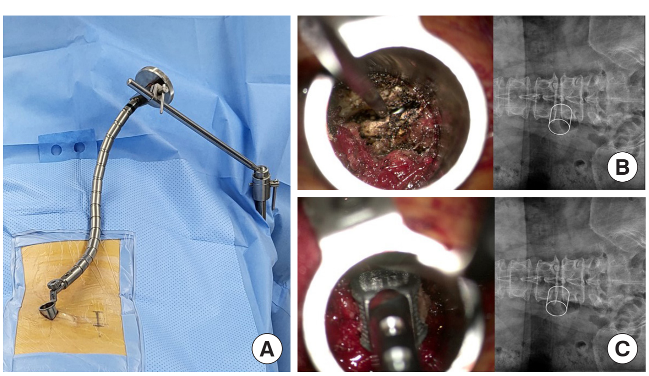

Fig. 1. (A) Standard set-up for tubular retractor. Surgical view during minimally invasive transforaminal lumbar interbody fusion with tubular retractor. Facet joint (B) and interbody cage insertion (C).

However, tubular retractors require a microscope, and full ESS causes rapid surgeon fatigue, resulting in dangerous situations due to the narrow field limitation.[23] Full ESS is performed through a single portal through which passes the light source, irrigation visualization, and the surgical instruments.[24] Unilateral biportal endoscopic (UBE) spine surgery has been introduced and become widely accepted due to the familiar surgical view and allowing the surgeon free dexterity.[25] In 1996, De Antoni et al.[26] published the first technical note in which endoscopes and instruments were inserted independently through 2 portals. Two years later, they described the use of standard arthroscopic instruments for magnification, illumination, and irrigation and reported good clinical results.[27] Soliman published surgical results for lumbar disc herniation and spinal stenosis in 2013 and 2015, using UBE techniques with independent portals, which is very similar to current methods (Fig. 2).[28,29] UBE surgery offers low blood loss, early discharge, familiar working space, and a wide view.[25,29]

CURRENT ROLE OF ESS

1. Lumbar Spine

1) Transforaminal approach

Transforaminal approach is the most traditional method used in ESS for discectomy. The endoscope is inserted towards Kambin's triangle. The most important parts of the approach are safe docking and placing the spine endoscope under fluoroscopic guidance.[30] The surgeon must have excellent understanding of radiologic imaging and of the patient's anatomic restrictions, such as the iliac crest at the level of L5/S1. With improvements

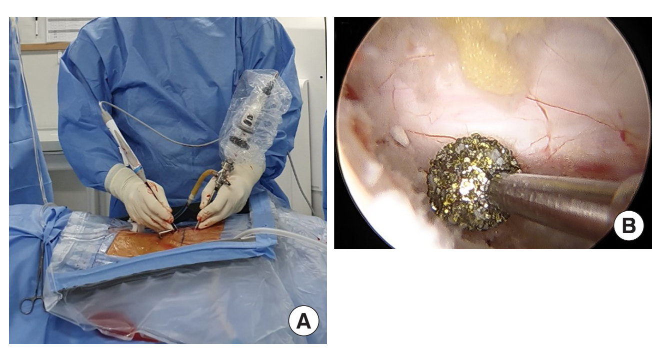

Fig. 2. Overview of unilateral biportal endoscopic spine surgery (A) and operative view (B). Surgical instruments (drills, etc.) could move independently in the endoscope view field.

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in ESS equipment, many studies demonstrated that complex cases of migrated discs also could be treated with partial resection of the pedicle and foramen.[31,32] Osman reported in a cadaveric study that the transforaminal technique resulted more expansion of foraminal space and less instability.[33] In foraminal stenosis patients, the transforaminal approach is successful and has good long-term outcomes.[34] A recent cadaveric study demonstrated that extensive foraminotomy in lateral recess with removal of the ligamentum flavum and superior articular facet is feasible.[35,36]

Transforaminal endoscopic surgery could be an option for revision surgery, and transforaminal decompression of foraminal or lateral recess stenosis in patients with previous spinal surgery resulted in excellent or good outcomes after 2-year follow-up.[37] Yagi et al.[38] evaluated 48 consecutive patients who underwent previous spine surgery and performed revision surgery with the transforaminal endoscopic approach under local anesthesia, reporting successful outcomes. Several recent studies have reported that there were no significant differences in reoperation and complication rates between transforaminal endoscopic surgery and open microscopic surgery, but the endoscopic group showed less back pain postoperatively and shorter length of hospital stay.[4] Because of the shorter operation time, the transforaminal approach can be performed as awake surgery. Telfeian et al.[39] reported successful clinical outcomes after awake transforaminal endoscopic lumbar surgery in 52 consecutive patients over the age of 80.

2) Interlaminar approach

Transforaminal approaches can yield successful decompression in cases of posterolateral disc herniation and foraminal stenosis, but have limitations for the treatment of central stenosis. This limitation inspired the use of endoscopes for interlaminar approaches.[40,41] Interlaminar techniques provides surgeons with more familiar visualization similar to conventional open surgery. Previously, transforaminal ESS was mainly performed for discectomy. With the development of the interlaminar approach, ESS has been applied to the surgical treatment of various stenoses, including central stenosis. In interlaminar approaches, using endoscopes helps preserve the bony anatomy and bilateral facet joints better than conventional open surgery.

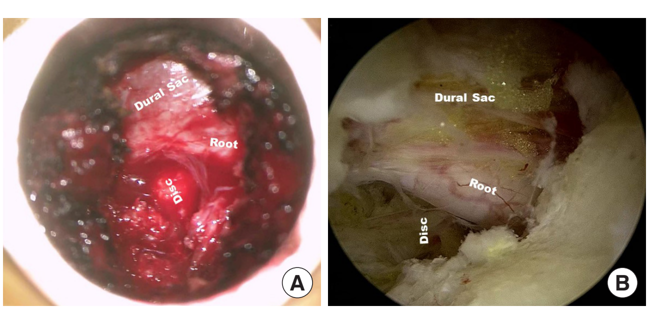

Fig. 3. Visualization with tubular retractor (A) and spine endoscope (B). Due to zoom-in effects during endoscopic spine surgery, endoscopic spine surgery showed similar or superior resolution to conventional approaches.

Because of the high resolution due to zoom-in effects, ESS showed similar or superior results compared to tubular retractor and conventional discectomy and decompression (Fig. 3).[4] A prior study analyzed 95 consecutive patients who underwent either tubular surgery or endoscopic decompression. The endoscopic group had better clinical outcomes and shorter length of hospital stay, fewer complications, and fewer revisions.[42] Ruetten et al.[43] performed a randomized controlled trial of 161 patients who underwent either endoscopic or conventional microscopic interlaminar decompression for lateral recess stenosis and found similar symptomatic recovery but lower rates of revisions and complications in endoscopic surgery patients. Lee at al.[44] published a meta-analysis of 5 retrospective cohort studies involving 156 patients with neurogenic claudication due to central stenosis. Their results demonstrated significant improvements in Oswestry Disability Index (ODI) and visual analogue scale (VAS) scores.

Some prior studies compared full endoscopic and UBE surgeries. Hua et al.[45] compared clinical outcomes of 2 endoscopic surgeries, and reported that the safety and efficacy of both procedures were similar, but operation time was shorter and central canal decompression was better in UBE surgery. Heo et al.[46] compared 3 different types of minimally invasive decompressive surgery for central stenosis, and found that patients treated with full ESS complained less of postoperative pain while those treated with UBE showed less violation of the facet joints. There remains much room for improvement, but endoscopic techniques have proven their potential and role in spine surgery.

3) Lumbar interbody fusion

Minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) with tubular retractor procedures have become more popular due to minimal disruption and faster recovery.[21] For the same reasons, endoscopic lumbar interbody fusion is gaining attention, especially in elderly and highly morbid patients. In patients with unilateral foraminal stenosis and mild to moderate central stenosis, endoscopic fusion could be an attractive option; however, patients with bilateral foraminal stenosis, severe central stenosis, or high-grade spondylolisthesis still have limitations for endoscopic lumbar interbody fusion.[5,47]

The endoscopic transforaminal lumbar interbody fusion (TLIF) approach is almost the same as the MIS-TLIF technique. In addition, both full ESS and biportal endoscopic techniques could be applied in lumbar interbody fusion surgery. After docking instruments, laminotomy with central decompression is performed.[48] Unlike simple decompression or discectomy under endoscope, an ipsilateral facet should be totally removed to create working space for endplate preparation and cage insertion (Fig. 4).[3,49]

Many clinical studies have shown successful outcomes of endoscopic interbody fusion. Recent studies found that biportal endoscopic TLIF and MIS-TLIF showed no significant differences in clinical outcomes.[50-52] Patients who undergo uniportal endoscopic fusion have better recovery, less demand for opioids, early mobilization, and shorter length of hospital stay.[47] There are no significant differences in early and midterm postoperative outcomes and fusion rates between biportal and full endoscopic fusion groups.[53] However, no prior research has reported long-term fusion rates over 2 years.[48] Long-term outcomes and randomized controlled trials still remain to be performed.

2. Cervical Spine

Recently, application of endoscopic techniques in cervical degenerative spine disease has increased. Endoscopic surgery is now used for both anterior and posterior approaches. Posterior full endoscopic cervical foraminotomy and additional discectomy showed similar clinical outcomes to conventional anterior cervical discectomy and fusion.[54] Guo et al.[55] published a meta-analysis of 24 studies that supported the efficacy and safety of posterior endoscopic keyhole surgery compared to conventional anterior cervical discectomy and fusion. Cervical motion was preserved better in posterior full endoscopic cervical foraminotomy and discectomy, but the surgical indication is narrower.[56] Patients who underwent endoscopic surgery had less blood loss, shorter operation times, and shorter hospital stays than those treated with conventional open foraminotomy.[57] Cervical myelopathy was thought to be a contraindication of endoscopic cervical spine surgery, but recently, with the development of large-size full endoscopes and UBE, endoscopic laminectomy has also become possible.[58,59]

Anterior cervical discectomy and fusion (ACDF) has been the gold standard of surgical technique in cervical disc herniation. Several recent studies showed good clinical outcomes of

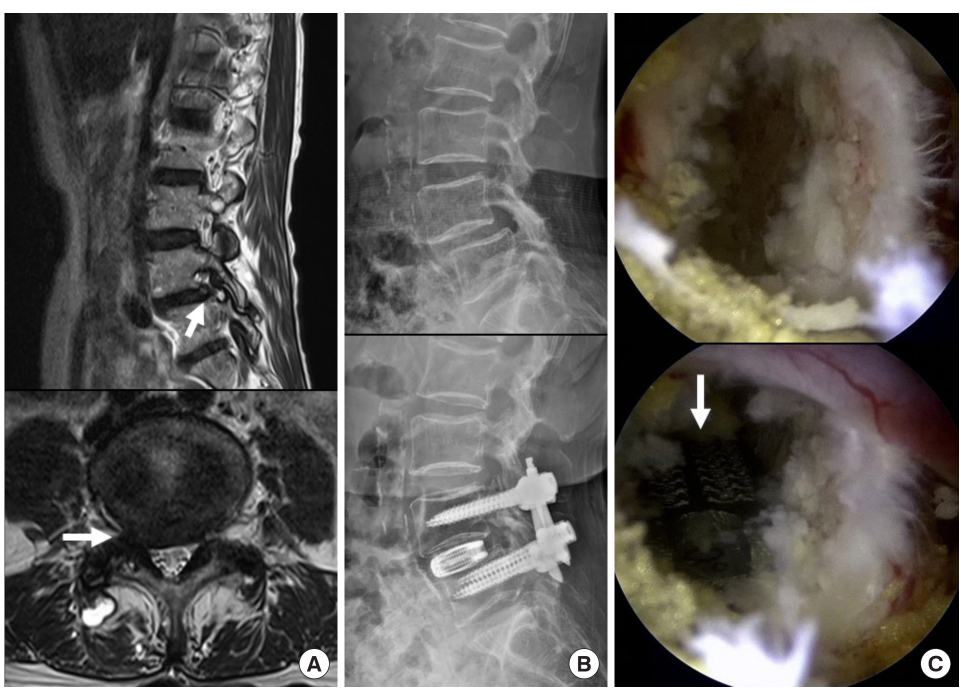

Fig. 4. Biportal endoscopic transforaminal lumbar interbody fusion (TLIF). (A) Preoperative magnetic resonance images showed degenerative spondylolisthesis L4 on L5 with right foraminal stenosis (arrow). The patient underwent biportal endoscopic TLIF. (B) Preoperative and postoperative lateral x-rays showed spondylolisthesis was reduced well with interbody cage and percutaneous pedicle screw fixation. (C) Endoscopic images show complete discectomy and endplate preparation and inserted titanium cage (arrow).

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anterior full endoscopic cervical discectomy in patients with soft disc herniation, unilateral radiculopathy, and central or paracentral disc herniation.[6,60] Ahn et al.[61] reported 5-year follow-up outcomes of anterior full endoscopic discectomy for soft disc herniation and showed comparable results with conventional ACDF. Zhang et al.[62] performed a meta-analysis and demonstrated successful clinical outcomes and shorter operation time and hospital stay than conventional ACDF. Recently, full endoscopic ACDF was attempted, but no relevant research has been reported yet, and few studies are being attempted (Fig. 5).

Recently, studies have described endoscopic surgery with screw fixation. Zhu et al.[63,64] attempted the posterior UBE approach for cervical stenosis and performed decompressive laminectomy and unilateral lateral mass screw fixation, and reported that open-door laminoplasty also was possible with UBE. Lvov et al.[65] reported endoscope-assisted posterior transarticular standalone screw fixation of C1–2 in traumatic injury patients, and found better pain scale recovery after surgery, less blood loss, and shorter operation time. Kotheeranurak et al.[66] announced a novel technique of full endoscopic anterior odontoid screw fixation, and reported successful outcomes in 4 traumatic injury cases.

3. Thoracic Spine

Because of the lower incidence of thoracic degenerative spine conditions, there is little relevant research. Many conventional thoracic spine approaches exist, but the majority require extensive resection of ribs and soft tissues, and are accompanied by various complications including intensive care unit stays and pulmonary dysfunction.[67,68] To overcome complications of the conventional thoracic approach, Choi et al.[69] studied transforaminal full endoscopic thoracic discectomy in 14 patients with thoracic soft disc herniation and 5-year follow-up. They reported significant improvements in VAS and ODI scores. Ruetten et al.[7] studied 55 patients with thoracic disc herniation treated using a full-endoscope technique via interlaminar, extraforaminal, or transthoracic retropleural approaches, and found that sufficient decompression was achieved and no serious complications in their patients.

Although ESS is still a challenging surgery for thoracic myelopathy, Cheng and Chen[70] reported 12 consecutive cases of full endoscopic thoracic decompression for thoracic spinal stenosis. They used both transforaminal and interlaminar approaches and reported successful clinical outcomes. Shen et al.[71] also studied 360° full endoscopic decompression for thoracic spinal stenosis with myelopathy, with simultaneous transfo-

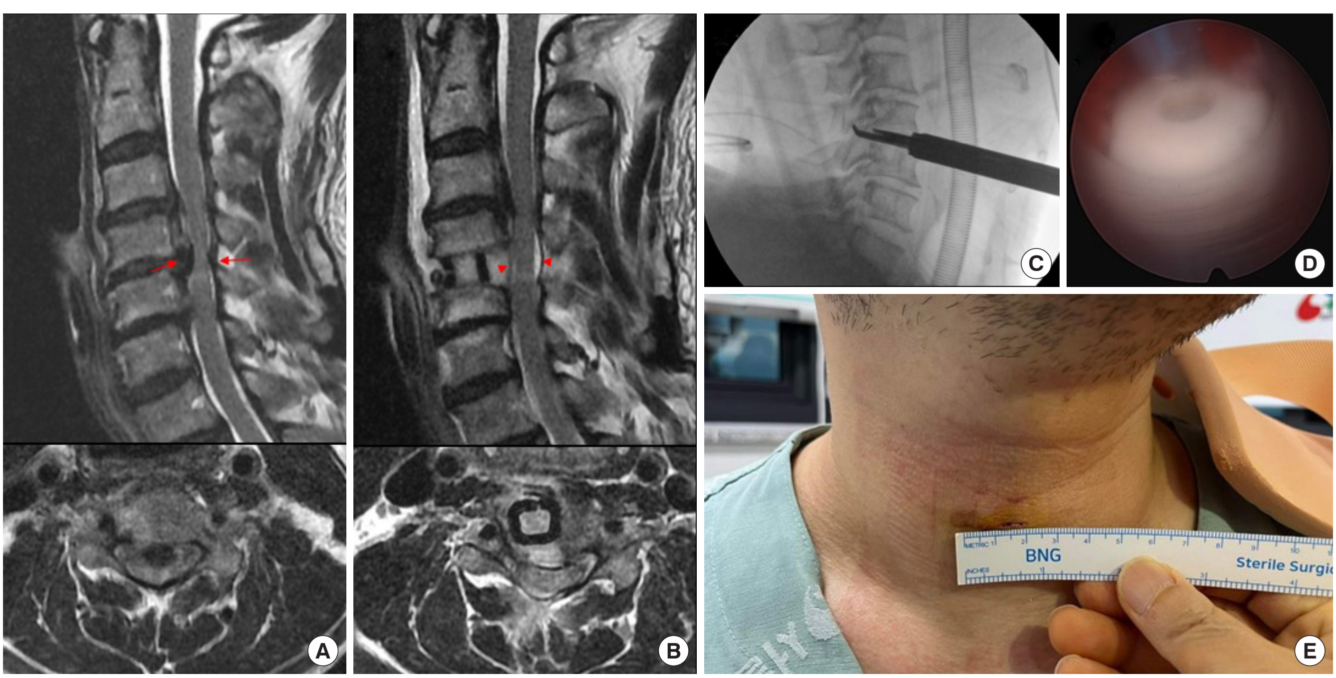

Fig. 5. A cervical ossification of the posterior longitudinal ligament patient underwent full endoscopic cervical discectomy and fusion. Preoperative (A) and postoperative magnetic resonance images (B). C-arm lateral image (C) during foraminotomy and operative view after cage insertion (D). (E) Final wound was about 2 cm. All images were provided by Dr. Kangtaek Lim.

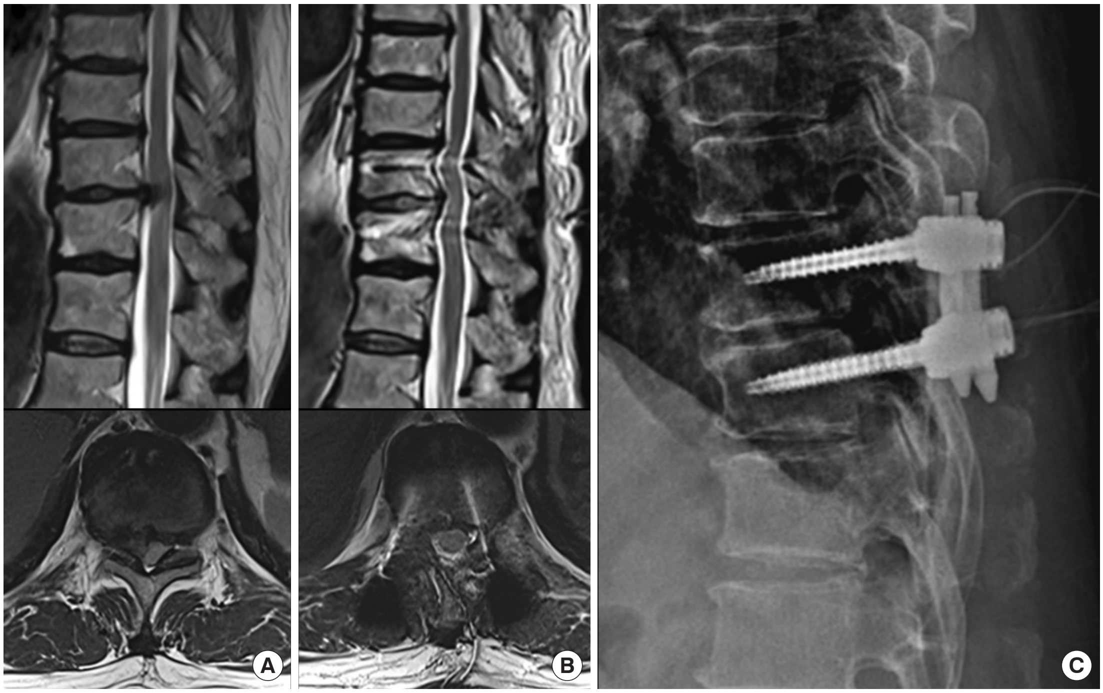

Fig. 6. Thoracic disc herniation with myelopathy in T10–11 underwent thoracic discectomy and postero-lateral fusion by unilateral biportal endoscopic surgery. Preoperative (A) and postoperative magnetic resonance images (B). Postoperative x-ray (C) showed screw fixation. All images were provided by Dr. Mankyu Park.

raminal and interlaminar full endoscopic decompression, and reported favorable results.

Although some studies reveal good outcomes of endoscopic approaches in the thoracic spine, endoscopic techniques for thoracic spine surgery are limited and remain challenging because of the complexity of thoracic spine anatomy, including ribs, lung, pleura and great vessels, and risk of catastrophic injury, such as paraplegia.[69,72] However, with the development of UBE techniques, ESS is a potential treatment for thoracic myelopathy accomplished by ossification of the ligamentum flavum, and fusion surgery for the thoracic spine is also being attempted (Fig. 6).[73]

ADVANCED TECHNIQUES AND FUTURE DIRECTIONS FOR ESS

1. Navigation

Endoscopic surgery has a steep learning curve and involves difficulty in anatomy visualization. Recently, many attempts have been made to introduce navigation systems into ESS. Navigation provides highly accurate real-time anatomical information and guidance for instrument placement, for which 2-dimensional (2D) fluoroscopy is insufficient.[74] Intraoperative computed tomography scans and guidance are safe and effective alternatives to fluoroscopy.[75,76] Navigation with an intraoperative O-arm in conventional spine surgery allows high accuracy of pedicle screw placement and reduces complications and revisions.[77-80] In ESS, this navigation system could help operators calculate an optimal trajectory and find ideal incision points in the early stages of surgery, and help confirm the exact locations of surgical instruments during UBE and full ESS (Figs. 7, 8).[81-84] Quillo-Olvera et al.[85] reported the possibility of increasing safety and accuracy by using navigation for pedicle screw fixation as well as accurate positioning of endoscopic instruments by using navigation for TLIF with biportal endoscope.

Standard navigation techniques require optic tracers, which takes up space during ESS (Fig. 7). To overcome this weakness, electromagnetic navigation (EMN) systems may be applied to full ESS, and a randomized controlled trial with EMN demonstrated similar clinical improvement and lower radiation exposure levels for both options.[86] Another retrospective study found that the use of the EMN system significantly reduced operation time and radiation exposure.[87] Navigation systems could provide greater safety and accuracy, and help overcome the steep learning curve of ESS.

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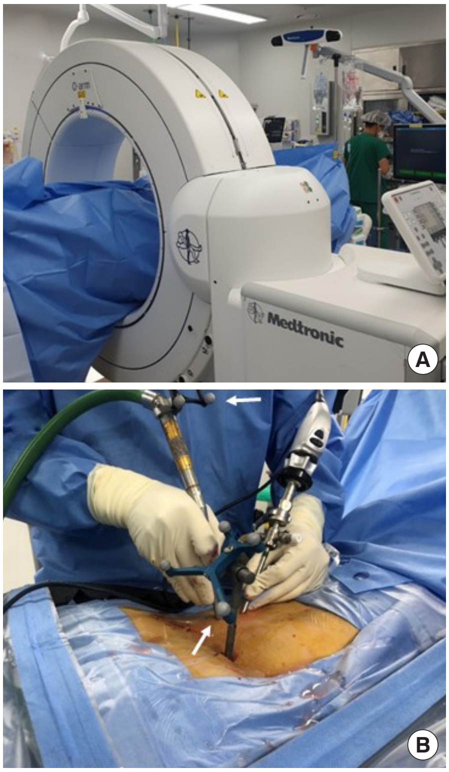


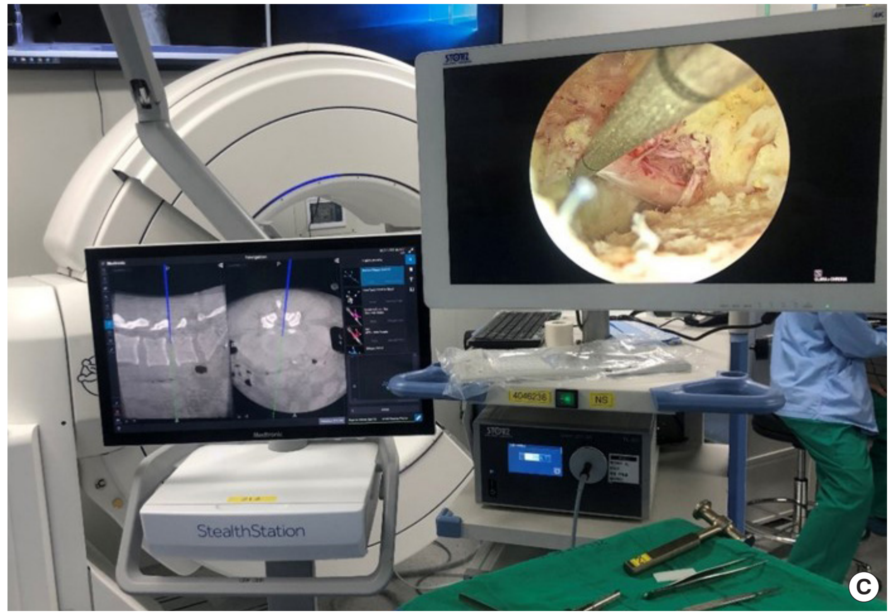
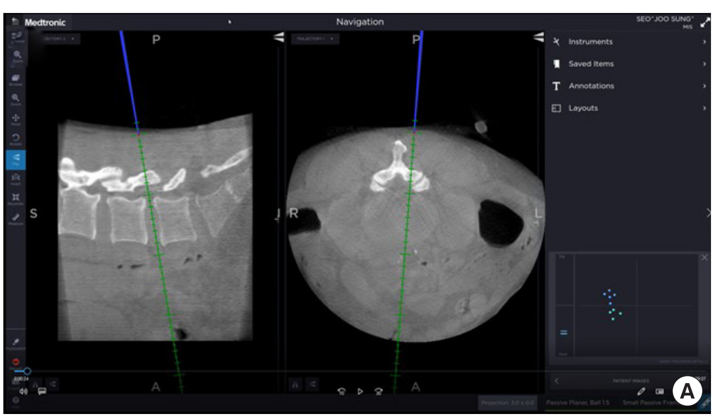


Fig. 7. Biportal endoscopic surgery with navigation. The use of fluoroscope during endoscopic spine surgery could be replaced by navigation-assisted endoscopic surgery. An O-arm (A) is needed to apply navigation-assisted endoscopic surgery. Operation field with optical tracer (B), navigation and endoscope monitor (C).



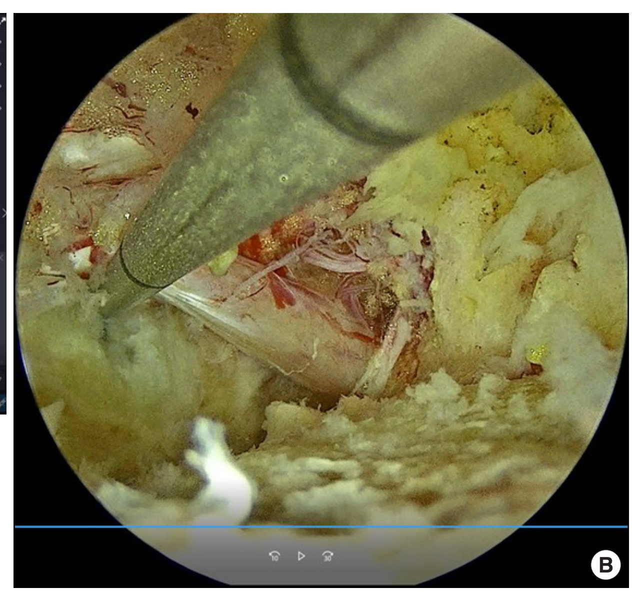


Fig. 8. Real-time tracking of surgical instruments during navigation-assisted biportal endoscopic spine surgery. Navigation image (A) and endoscopic image (B). Instrument tip is located inside the disc.

2. Augmented Reality and Virtual Reality

Augmented reality (AR) is an interactive experience that combines the real world and computer-generated content. This novel technology is infiltrating healthcare and spine surgery. AR systems mainly serve as navigation tools in operating rooms.[88] Standard navigation systems have limitations in simultaneous visualization, while head-mounted displays allow visualization of the surgical field and navigation data at the same time. AR helps reduce radiation exposure and operation time, and also provides safety and precision to beginners during pedicle screw fixation.[89-91] Molina et al.[91] studied the application of AR in pedicle screw fixation in a cadaveric model, and demonstrated that AR-assisted procedure is superior to free-hand techniques. AR assistants could be utilized not only for pedicle screw fixation, but also for finding the ideal trajectory and entry points like standard navigation systems in ESS.

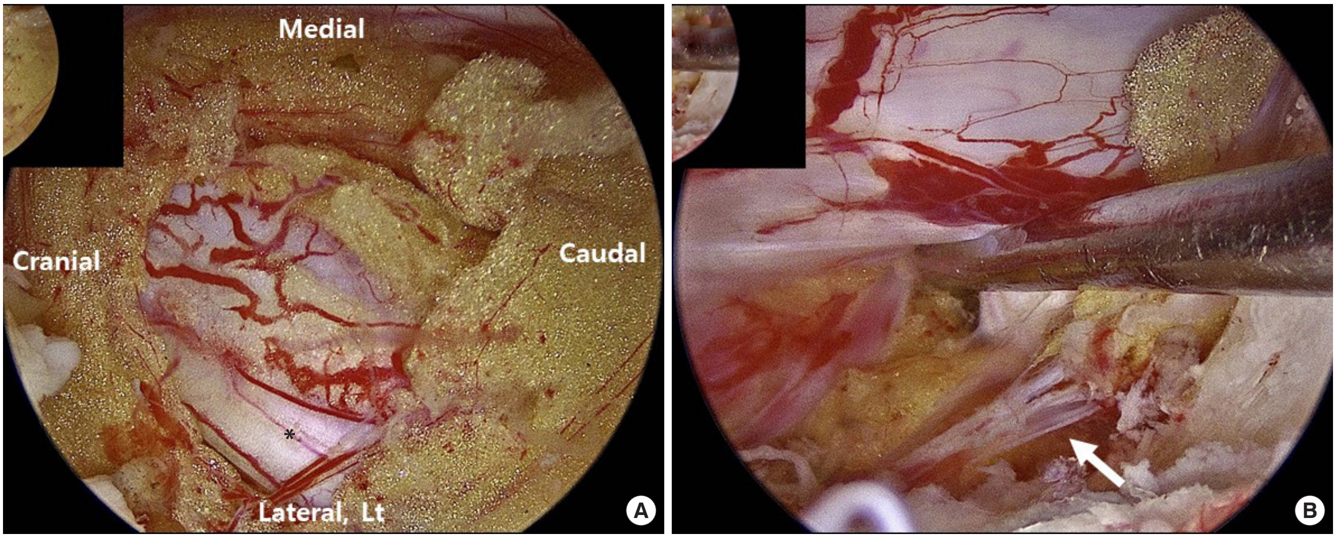


Fig. 9. Excellent visualization provided by a 4K ultraresolution endoscope. In particular, since it is possible to zoom-in closer to the lesion with ultraresolution, a more detailed view can be seen compared to conventional surgery. Left S1 root (asterisk) is well recognized with surrounding blood vessels and epidural fat (A), and tiny structures like foraminal ligaments are visible (arrow) (B).

Virtual reality (VR) is a highly advanced technology that allows surgeons to experience surgery in a virtual world created by a computer. VR stimulators are gaining attention in education and preoperative planning. Zheng et al.[92] reported that a VR preoperative planning system for full ESS could significantly improve accuracy and reduce operation times. Since ESS is performed with a monitor, it is an ideal surgery for VR education, which could help overcome the steep learning curve.

3. Robot-Assisted Surgery

Robot-assisted surgery is expanding in many surgical fields. Robot-assisted spine surgery is usually performed for pedicle screw fixation, and recent studies suggested that robot-assisted screw fixation has higher accuracy, shorter hospital stay, and lower radiation exposure than surgeries without robots.[83] Gao et al.[93] found that robot-assisted percutaneous pedicle screw fixation could be performed under regional anesthesia effectively and safely. Robots can place pedicle screws in precise positions, and robot-assisted spine surgery shares overlapping features with navigation systems. However, robots provide exact physical guidance to conduct preoperatively customized surgical plans. Therefore, the ESS also could apply robot-assisted for to accurate positioning of endoscopes at ideal locations. Wang et al.[94] applied robot assistance in full endoscopic lumbar discectomy and validated its safety and effectiveness as an alternative to conventional fluoroscopic ESS. Robot-assisted ESS is also expected to help overcome steep learning curves by helping to put the endoscope in the correct position.

4. Ultraresolution (4K) and 3-Dimensional and Ultraresolution Endoscope Applications

Current 2D ESS has disadvantages due to lack of stereoscopic vision. Lack of depth perception causes unfamiliarity with surgical anatomy and influences the perioperative complications. Three-dimensional (3D) endoscopic equipment provides clear views of surgical anatomy, such as exposure of dura and nerve roots. Three-dimensional images can make surgeons feel dizzy, but have advantages for reducing learning periods and distinguishing lesions from normal neural structures.[95] The adoption of ultraresolution and 3D images for ESS could enable surgeons to identify surgical anatomy more precisely, reducing unintended damage to vulnerable structures. Using a 4K ultraresolution endoscope, structures such as foraminal ligaments, which are difficult to observe with conventional microscopes, can be easily identified (Fig. 9). Furthermore, accurate perception of the degree of stenosis and disc protrusion using 3D visualization could reduce surgical uncertainty, followed by better decompression of neural structures and better surgical outcomes.

CONCLUSION

ESS has rapidly grown over the last 30 years. Although it was first introduced in the lumbar spine, ESS is now being applied to whole spine surgery, including the cervical and thoracic spine.

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Table 1. Possible surgeries according to endoscopic spine surgery technique

Location and type of surgery	Full endoscopy	Biportal endoscopy
Cervical		
Anterior approach		
ACDF with stand-along cage	O	X
Discectomy and foraminotomy	O	X
Odontoid screw fixation	O	X
Posterior approach		
Foraminotomy and discectomy	O	O
Central decompressive laminectomy	O	O
Lateral mass screw fixation	X	O
Laminoplasty	X	O
Thoracolumbar		
Posterior approach		
Central decompressive laminectomy	O	O
OLF removal	O	O
Foraminal decompression	O	O
Disectomy	O	O
Interbody fusion	O	O
Tumor		
Extradural tumor	X	O
Intradural tumor	X	X

ESS has mainly been applied to disc herniation, but has been extended to other pathologies such as spinal stenosis and myelopathy. It was chiefly used for simple nerve decompression, but with the recent development of percutaneous screw fixation systems, almost all kinds of fusion surgery including cervical, thoracic, and lumbar spine fusion have become possible with ESS. The removal of extradural tumors has also been achieved with biportal ESS. However, the application of ESS to major areas of spine surgery other than degenerative diseases, including deformities and intra-dural tumors, is still limited (Table 1).[96,97] ESS is cutting edge spine surgery that can take advantage of various technologies, with the latest technologies including navigation, AR, VR, robots, and 3D image already having been adopted.

As the number of elderly and highly complicated patients continues to increase, ESS will become more important for MISS in the future. Further efforts to improve ESS techniques and apply new technologies will place ESS among the best options for surgical treatment of entire spine diseases by overcoming current limitations.

NOTES

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