The Evolution of Transforaminal Endoscopic Spine Surgery
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Transforaminal endoscopic spine surgery (T-ESS) has become a well-accepted technique. The first attempts at percutaneous discectomy by Kambin and Hijikata opened a new chapter of endoscopic spine surgery. By the last quarter of the twentieth century, spine surgeons had begun to adopt this novel technique. Many researchers helped advance endoscopic spine surgery, but the turning point was the description of a safe transforaminal triangle of safety by Parviz Kambin. Since then, the indications for T-ESS have increased as a result of the description of different surgical approaches such as inside-out, outside-in, and half-and-half. We present a review of crucial historical advancements in T-ESS and also discuss the evolution of endoscopes, the techniques used, development of endoscopic instruments and equipment, transforaminal thoracic endoscopy, transforaminal endoscopic interbody fusions, the growth of extended indications, and the future direction of T-ESS. This review provides a detailed description of key historical moments and a bird’s-eye view of the vast scope of T-ESS.

INTRODUCTION

Spine surgery for the surgical management of lumbar disc herniation (LDH) has considerably changed since Mixter and Barr (Figure 3A) first described open discectomy in 1934. Progressive improvements in spine surgery over the following decades gradually minimized the size of skin incision and gave birth to spine minimally invasive surgery (MIS). Open discectomy followed by microdiscectomy, percutaneous nucleotomy, tubular discectomy using tubular dilators, and the introduction of a camera and multichannel endoscope with saline irrigation by Yeung gave rise to endoscopic spine surgery (ESS). A recent meta-analysis concluded that percutaneous endoscopic lumbar discectomy (PELD) has lower overall complications compared with open discectomy and microdiscectomy. Hence, over time, more surgeons will opt for PELD to deliver state-of-the-art care to their patients.

This review provides a detailed description of key historical moments and a bird’s-eye view of the vast scope of transforaminal-ESS (T-ESS) and excludes the outcomes, complications, and the learning curve.

Decade-Wise Evolution of T-ESS

The timeline in the evolution of T-ESS can be expressed in decades, from the nineteenth century to the twenty-first century AD (Figure 1). The history of T-ESS has undergone dramatic changes as indicated by Figure 2.

1) The end of the nineteenth century is marked by the invention of the light bulb by one of the greatest inventors, Edison (Figure 3B). The year was 1879 and the place, Menlo Park, California, USA, when after thousands of attempts and failures, Edison invented a light bulb that stayed illuminated for almost 13 hours. Good illumination is the soul of any endoscopic procedure, and ESS is no exception.

2) The next significant discovery is credited to Hopkins (Figure 3C), who in 1959 developed rod lenses for endoscopy, and Karl Storz (Figure 3D), who redefined the illumination of body cavities under the name cold-light source.

In the same year, Dr. Irving Ellman (Figure 3E), a dentist, developed the first...
Figure 1. The timeline in the evolution of transfominal endoscopic spine surgery with inventors from the nineteenth to the twenty-first century. CPT, Current Procedural Technology; ESS, endoscopic spine surgery; MISS, minimally invasive spine surgery; PELD, percutaneous endoscopic lumbar discectomy; THESSYS, Thomas Hoogland Endoscopic Spine System; YESS, Yeung Endoscopic Spine System.

Figure 2. Evolution of endoscopes from the prebranding era to the era of hyperactivity. THESSYS, Thomas Hoogland Endoscopic Spine System; YESS, Yeung Endoscopic Spine System.
Surgi-Max radiofrequency generator, which continues to deliver a unique brand of radiofrequency energy of very high frequency and low heat with virtually no collateral heat spread or tissue damage.6-8,10 Also, in 1958, Watanabe (Figure 3F), a Japanese orthopedic surgeon, developed and used the first arthroscope with a superior handmade lens system.9

3) The invention of an imaging-semiconductor circuit (the charge-coupled device sensor) in 1969 was the next stepping stone in the evolution of ESS. The inventors, Boyle and Smith, received a Nobel prize for the invention and its broad applicability in technology.5-8

4) The march toward ESS started with the introduction of the Craig cannula (Figure 4) to perform a percutaneous lateral discectomy by Kambin in 1973 and by percutaneous nucleotomy by Hijikata, who introduced cannulas to perform the procedure in 1975.5,6,10-12 This age is also illuminated by the merit of Schreiber, who introduced the idea of staining the nucleus pulposus with indigo carmine dye.13

5) The 1990s in ESS began with the introduction of a foraminoscope by Hans Jörg Leu in 1991.6 The Leu foraminoscope remained in the market for 21 years. Although Kambin introduced lasers in 1990,14 they were popularized by Mayer and Brock in 1992, who introduced the term PELD.15

6) The second half of the 1990s in the evolution of endoscopy began with the introduction of a 30° endoscope by Kambin and Zhou in 1997 followed by the evolution of microendoscopic approaches using tubular dilators and endoscopic camera systems by Foley et al. for far lateral LDH.5,16 Simultaneously in 1996, Mathews17 introduced his 0 foraminoscope, which was followed by Ditsworth in 1998.58

7) Revolution in endoscopy happened with the development of YESS (Yeung Endoscopic Spine System)19 and THESYS (Thomas Hoogland Endoscopic Spine System).20,21 These multichannel endoscopes, which were developed around the end of the twentieth century, primarily use the inside-out or the outside-in technique.

8) The first 20 years of the twenty-first century for T-ESS are marked with the concept of full-endoscopy developed by Rutten et al. in 2006.22 The trailblazers of South Korea, Choi, Ahn, Kim, and others, described the use of endoscopic burrs in 2008 and changed the way the scientific world looked at foraminotomy and foraminoplasty.18 Since Joimax (Joimax GmbH, Germany) launched the endoscopic system in China in 2006, many endoscopic cases have been performed under the leadership of Zhang and Zhou.24,25 Endoscopy has been also slowly used in the United States, with recognition of an official Current Procedural Terminology code 62380 on January 1, 2017.26 Based
on the inclusion of the newly created American Medical Association Current Procedural Terminology code 62380 in the United States, and the worldwide increasing adoption rate of ESS in general, the companies of endoscopic spine surgeries are gaining a strong foothold throughout the United States. The acceptance of surgical techniques of ESS and their benefits to both patients and surgeons is increasing steadily in Europe and the United States and more rapidly in South Asia and Latin America.

One of the most significant steps in the evolution of T-ESS is the 2018 integration of endoscopy in the official curriculum of spine MIS for spine surgeons by the AO Spine MIS Task Force. 17

ESS has progressed from the transfemoral corridor to the interlaminar corridor and covers extended indications such as central and lateral recess stenosis and L5-S1 discectomy. 4,10,16

Newer endoscopes with increased internal diameter help in addressing central stenosis with less morbidity compared with microscopic approaches for decompression. This review article focuses on the evolution of T-ESS since Kambin and Hiijikata described the lateral percutaneous discectomy until the present day and upcoming future trends.

EVOLUTION OF LUMBAR DISC SURGERY FROM OPEN LAMINECTOMY TO SPINE MIS AND ESS

Krause and Oppenheim (Figure 3E) described the first lumbar discectomy in 1909 but named the disc fragment as a chondroma. 3 Goldthwaite in 1911 closely followed with a description of a case of sciatica and paraplegia, which he attributed to the posterior displacement of an intervertebral disc; he proposed that such herniations may be a common cause of sciatica. 1 Adson in 1923 gave the first description of the surgical removal of a herniated nucleus pulposus. 1,2 However, Mixter and Barr, who reported the first case series of surgical removal of herniated discs in 1934, are credited as the first disc surgeons. 1,2,4,11,12 Nevertheless, their procedure was an open laminectomy and, in cases of central disc herniation involved a transdural approach to the herniation. The morbidity associated with this approach was evident from the beginning, and in 1939, Love (Figure 3H) described a less morbid interlaminar approach to disc herniation. 3 This approach to LDHs remained the gold standard in subsequent decades.

Smith, 39 after he observed cartilage dissolution in rabbit ears after administration of chymopapain, proposed intradiscal use of this enzyme and described chemonucleolysis. Intradiscal administration of chymopapain was a disruptive technology in 1963. Still, it took another 19 years to receive approval from the U.S. Food and Drug Administration, in 1982. Percutaneous insertion of an enzyme to dissolve the disc material in contained herniations made it possible to avoid open surgery and mechanical removal of disc fragments in selected cases.

Valls and Craig independently described the posterolateral approach to vertebral bodies in 1948 and 1956, respectively. 14-16 Craig 16 described the vertebral body biopsy using a set of 3.5-mm internal diameter cannula under radiographic control and reported his results in Journal of Bone and Joint Surgery. Later, Kambin (Figure 5A) became interested in the feasibility of performing a percutaneous lateral discectomy using a similar surgical approach. In 1973, Kambin was operating on a patient with L3-L4 and L4-L5 herniation. After the laminectomy, he found only a small bulge at the L4-L5 level. Instead of making a window in the posterior longitudinal ligament and performing a discectomy, he introduced a Craig cannula laterally into the L4-L5 disc space and performed the first percutaneous decompression and discectomy. 14,15 Hiijikata (Figure 5B), a Japanese surgeon, was fascinated by the posterolateral approach to the disc space in the era of diagnostic discographies. He developed his cannulas and trephines with a 2.6-mm diameter and performed a lateral percutaneous nucleotomy with special pituitary rongeurs. He reported a 64% success rate in 14 patients and reported his findings in a regional scientific journal in 1975. 2,4,10,12,13,31 The pioneering work of Kambin and Hiijikata laid down the basis of lateral percutaneous discectomy, which further evolved into visualized endoscopic discectomy in subsequent decades.

Kambin and Gelman reported their series of 9 patients with LDH at the L3-4 and L4-5 levels. 20 They performed a percutaneous lateral discectomy using a modified cannula of 1.45 cm length and an internal diameter of 4.5 mm under fluoroscopic control. The results of this series reported in 1983 were complete pain relief in all 9 patients. The investigators advocated that producing a lateral window on the annulus may exert a prophylactic effect of intradiscal pressure and thus reduce the probability of a posterior herniation. This concept was revolutionary and laid the foundation for the further development of T-ESS.

Forst and Hausmann 26 in their series in 1983 reported the first photographic documentation of colored pictures of the intradiscal space after an open nucleotomy. They used a 4-mm internal diameter arthroscope with a stab lens system with fiberglass light conductors and various angled optics. These investigators termed this procedure nucleoscopy, using intradiscally located optics for the first time. The investigators proposed that using nucleoscopy, the surgeon was able to watch the current disc space directly and hence control the nucleotomy. Also, Friedman 60 reported the results of percutaneous discectomy in 9 patients operated on using the Jacobson technique. Friedman made a 25.4-mm (1-in) incision over the iliac crest and
introduced a 40F chest tube. The disc material was removed after annulotomy. The instruments were introduced laterally, and Friedmann cautioned screening the patients for the identification of aberrant retroperitoneal structures with transaxial scanning and gastrografin.

Onik (Figure 5C) in 1985 introduced a blunt-tipped nucleotide or a mechanical aspiration probe and performed the first automated percutaneous nucleotomy.35 This nucleotide aspiration probe had a hybrid needle with a 2 mm diameter and 20.3 cm length and a single side port near its end with a cutting sleeve and saline irrigation mechanism. The cutting sleeve within the nucleotide helps to cut any stuck pieces of nucleus pulposus in the side port, and the saline irrigation system with vacuum removed the pieces. These investigators argued that the incidences of nerve root injury in the neural foramen would be less because of the reduced diameter of their blunt-tipped probe. They proposed that this technique of mechanical aspiration of the disc material would be better than chemonucleolysis because of the chances of anaphylaxis and incidences of transverse myelitis associated with the later technique.

Taking inspiration from Hijiakta, Schreiber and Suezawa (Figure 5D) adopted percutaneous nucleotomy in their department from 1979.36 In 1982, these investigators started using an arthroscope from the opposite side of the symptoms of sciatica from where the cannula instrumentation was introduced. They introduced telescoping European-sized cannulas with a maximum internal diameter of 7.2 mm and a length of 15 cm at the center of the disc and performed a discoscopy simultaneously from the contralateral side. The investigators also introduced indigo carmine dye intradiscally before the nucleotomy, thus facilitating the identification of the dye-stained nucleus pulposus by discoscopy. The technique was first reported in 1986, and they recorded good results in 72.5% of their 109 patients.37

In 1986 and 1987, Kambin et al.38 addressed the technical challenge of excising adequate disc material through a needle by a lateral percutaneous discectomy. These investigators introduced a 5-mm-diameter cannula intradiscally. They used flexible forceps to remove the disc material. This modification significantly increased the amount of disc material removed and improved the clinical results in their series of 50 patients. Kambin is also credited with his extensive work on cadavers and the discovery of the transforminal safe working corridor, which is rightly named the Kambin triangle.4,39 Reported in 1990, the boundaries of the Kambin triangle are formed anteriorly by the exiting nerve
root, medially by the traversing nerve root and thecal sac covered by the superior facet, and inferiorly by the superior end plate of the lower vertebra. The introduction of the Kambin triangle helped in the safe insertion of slightly higher-diameter cannulas and instruments without neural damage. It was one of the most important discoveries in the evolution of T-ESS. Kambin also reported discoscopic views in 1988. He stressed the need for endoscopic epidural visualization and started using lasers to vaporize the disc fragments in 1990. However, the enthusiasm for lasers was short lived because they resulted in a wide arc of deflection and neural injury, hence limiting adequate decompression.

**Development of Spinal Endoscopes**

After the description of the Kambin triangle, T-ESS left the familiar shores of the intradiscal indigo carmine-stained nucleus pulposus and started exploring the foramen. Mayer (Figure 5F) and Brock introduced an angled lenscope for a more dorsal visualization of the dorsal annulus in 1993. These investigators introduced the term percutaneous endoscopic lumbar discectomy, and the findings of their randomized study advocated that PELD is comparable and at times superior to microdiscectomy.

Leu (Figure 5E) designed a foraminoscope with Karl Storz in 1991 for foraminal and extraforaminal disc herniations. This foraminoscope had a length of 145 mm and an internal diameter of 3 mm, with a variety of instrument, and produced excellent image quality. This Leu-designed foraminoscope could be sterilized and reused, thus reducing the operating cost; it remained on the market for 21 years until 2012.

Mathews described foraminal epidural endoscopic surgery and introduced the first fiber-optic endoscope in cooperation with Danek Inc. (Memphis, Tennessee, USA) in 1996. The Danek foraminoscope was a 210-mm-long, 3.5-mm internal working channel diameter and an outer diameter of 6.5 mm but offered a viewing angle of only 60°. The foraminoscope was meant for median and paramedian herniations but was withdrawn from the market because of its inability to fit the foramen. 0° optics failing to deal with central disc herniations, poor image quality, and single-use system that increased the cost of the procedure.

However, Yeung (Figure 5G) applied the principles of joint arthroscopy (continuous saline irrigation and underwater bipolar dissection and suction) and introduced a multichannel, wide-angled endoscope. The system was named the Yeung Endoscopic Spine System (YESS) and was produced in collaboration with Richard Wolf (Figure 6). This endoscope was 207 mm long with a 2.7 mm internal diameter with a rod-lens and irrigation system. The system was designed for intradiscal decompression, extraforaminal, and foraminal disc herniations, and foraminotomy. The YESS system established itself with excellent image quality, cold-light projector, and a camera with a target for intradiscal and epiduroscopic procedures.

Hoogland (Figure 5H) after using the Danek foraminoscope found the shortcomings of nonusability in several indications (e.g., foraminal and extraforaminal herniations and patients with sequestration) and advocated the use of foraminoplasty. In 1994, he devised a system of reamers capable of performing a foraminoplasty and named it Tom-Shidi (Figure 7). He collaborated with Joimax and produced a multichannel endoscope with 180 mm working length, 3.6 mm inner diameter of the working channel, and a 0°–30° optic variant with an outer diameter of 6.3 mm. This system was named the Thomas Hoogland Endoscopic Spine System (THESSYS). This system offered the broadest range of coaxial endoscopes and variable length and diameter endoscopes.

**Evolution of T-ESS Techniques—The Inside-Out and Outside-In**

Kambin and Hijikata established the era of lateral percutaneous discectomy/nucleotomy with the center of the disc as the target. The first patients selected for these techniques were those with LDH with the principle of intradiscal debulking. Kambin and
Gellman\textsuperscript{34} even postulated that a lateral annulotomy would reduce the intradiscal pressure, thus decreasing the chances of a posterior disc herniation. Some investigators reported that a herniation at this lateral iatrogenic annulotomy site would not be significant because of a lack of neural structures. Hence, for the next 10–15 years, all the efforts in T-ESS were focused on positioning the cannula, aspirator, or the forceps safely inside the disc and performing a nuclear debulking. The indications for this strategy were limited to contained disc herniations, and patients with sequestered disc herniations, foraminal stenosis, and foraminal and extrarotaminal disc herniations were contraindicated.\textsuperscript{32–34} As experience with percutaneous lateral discectomy increased, several investigators realized the shortcomings of this strategy in common clinical presentations of disc herniations (e.g., sequestration). The need to improve the quality of care and reach the horizons and to expand the clinical application of T-ESS gave birth to the inside-out and outside-in techniques.\textsuperscript{42–47}

In 1990, Kambin described the safe transforaminal triangle and emphasized an intradiscal and epiduroscopic view for optimal decompression of the neural structures. After that, Mayer and Brock introduced their angled lenscope for more dorsal visualization of the annulus and thus started the development of the inside-out technique. The primary difference in the inside-out and outside-in technique is the primary location of the tip of the working cannula at the beginning of the surgery.\textsuperscript{47} With the inside-out technique, the tip of the cannula is primarily positioned anterior to the posterior annulus of the disc space separating the tip from the ventral dura, whereas with the outside-in technique, the tip of the working cannula rests at the neural foraminal posterolateral to the dural sac. Yeung popularized the inside-out technique with the YESS system, allowing instruments of $<2.5$ mm diameter intradiscally and allowing soft disc excision. The outside-in technique began with Hoogland’s desire to deal with foraminal stenosis and foraminal and intracanal herniations.\textsuperscript{42–44} He devised techniques to widen the foram with trephines and burrs. The proponents of the outside-in technique argued that the technique was well equipped to deal with both bony and soft tissue stenosis, giving it an edge over the traditional inside-out technique.\textsuperscript{42} This technique developed further with the evolution and introduction of thin-tipped high-speed endoscopic burrs introduced by Choi and other surgeons in 2008 to help in foraminoplasty, foraminotomy, pediculectomy, and osteophyte excision in selected cases under direct endoscopic visualization.\textsuperscript{23}

The half-and-half transforaminal technique was introduced in 2007 by Lee et al.\textsuperscript{45} for near-migrated disc herniations based on annular release and leveraging of the working sheath. This approach made the epidural space accessible to T-ESS. In this technique, a beveled working sheath is placed transversely from disc space to epidural space. The beveled edge of the working cannula is placed intradiscally, and a half-and-half view is obtained. In the dorsal view are the posterior longitudinal ligament, the traversing nerve root, and the thecal sac, whereas anteriorly, the intradiscal space is visualized simultaneously. The investigators also introduced an epiduroscopic technique for far-migrated disc herniations, by which they moved the working sheath from the disc space to the epidural space. Contrary to other countries, most endoscopic spine surgeons in Korea have followed the half-and-half technique.

The inside-out technique based on the YESS system and outside-in technique based on the THESSYS system share the same goal of removing the disc prolapse, so the argument over which method is more compelling looks meaningless. Moreover, most endoscopic experts have recently shared the point of view that performing customized surgery for the patient (e.g., determining the surgical technique based on the location of the hernia, presence of foraminal stenosis, and familiarity with a particular technique) rather than sticking to a particular system, can achieve the best results for the patient (Figure 8).

**EVOLUTION OF ENDOSCOPIES AND ENDOSCOPIC INSTRUMENTS AND TECHNOLOGY**

**Evolution of Endoscopes**

The feasibility of spinal endoscopy was first evident with the intradiscal introduction of a Craig cannula by Kambin. As technology advanced, researchers adopted the available instrumentations and
laid down the basis for ESS. Frost introduced an arthroscope intradiscally and reported the primary images. This development was followed by the reporting of discoscopic views by Kambin and dye-stained nucleus pulposus by Schreiber, the introduction of the foraminoscope by Lu, then the angled lens endoscope by Mayer and Broek, Danek foraminoscope by Matthews, 30 endoscopes by Kambin and Zhou, foraminoscope by Ditsworth, and the YESS and THESSYS systems by Yeung and Hoogland, respectively.14,15,17,19

**Evolution of Radiofrequency Ablators**

Ellman, a dentist, developed the first Surgi-Max (Ellquence LLC, New York, USA) radiofrequency generator, which continues to deliver a unique brand of radiofrequency energy of very high frequency and low heat with virtually no collateral heat spread or tissue damage.6,8

**Evolution of the Foraminal Reamers, Trephines, and Endoscopic Burrs**

After observing the shortcomings of the Danek foraminoscope, Hoogland noticed that foraminoplasty would be required to safely perform endoscopy and devised his set of foraminal reamers, named the Tom-Shidi system, which is still used. In 2008, Choi et al.73 introduced thin-tipped endoscopic burrs for foraminoplasty and foraminotomy.

**Modified Instruments for Outside-In Technique**

Recently, some investigators have reported new instruments and patented techniques for outside-in foraminoplasty. Performing a safe foraminoplasty is a skill set that requires years of experience and a demanding technique. The technique can be a painful and risky procedure because the exiting nerve root lies in the vicinity of the narrow foramen. The ZESSYS technique, introduced by Zhou et al., uses graded duck-mouth protective cannulas and graded trephines to perform a targeted foraminoplasty. In the ZESSYS technique, a K-wire or a needle is docked fluoroscopically at the posterior aspect of the caudal vertebra. The unique dual cannula design of the protective cannulas helps avoid injury to the exiting nerve root by the reamers (Figure 9).

A recent mobile outside-in technique described by Kim et al.44 focuses on the accurate placement of the cannula within the foramen rather than its enlargement. The technique is a slight modification of the half-and-half technique and uses the intervertebral route for central, paracentral, and high canal compromised LDH; the foraminal route for foraminal, superiorly migrated, and far lateral LDH, and the suprapedicular route for inferiorly migrated LDH.

**EVOLUTION OF T-ESS FUSION**

Recently, some investigators have reported the feasibility of a full-endoscopic technique for transformaminal lumbar interbody fusion (TLIF) through the Kambin triangle. The approach is similar to PELD and uses endoscopic visualization and high-speed burrs for interbody and end-plate preparation. An interbody cage is inserted through the same keyhole skin incision and trajectory of the working cannula. Endoscopic visualization and radiographic control guide the procedure, and resection of dorsal bony structures is avoided. Thus, fusion is achieved without damage to the multifidus muscle or bony structures. All these factors contribute to earlier functional recovery and maintaining spinal stability. Recently, Joimax has developed EndoLIF O-cages to be used along with TESSYS (transformaminal endoscopic surgical system). This osteoconductive cage is made of titanium, and a diamond cell structure has a high surface area that supports optimal bone ingrowth.

In 2013, Jacquot and Gastambide66 reported one of the most extensive series of percutaneous full-endoscopic lumbar interbody fusion (PELF) of 57 patients using rigid stand-alone cages. These investigators reported an unacceptably high complication...
rate, with 15 cage migrations requiring a reoperation and 8 patients with postoperative paresis and painful syndromes. The investigators did not recommend the PELIF technique in its current state. Considering the unacceptable rate of cage migration and subsidence, many investigators started using percutaneous pedicle screws along with PELIF.

In 2016, Wang and Grossman\textsuperscript{47} presented their series of 10 patients undergoing PELIF operated on with expandable cages and percutaneous pedicle screw insertion without general anesthesia. These investigators reported fusion in all cases without any complications and recommended this technique in a large patient population with long-term follow-up.

In 2017, Lee et al.\textsuperscript{48} reported a series of 18 cases of PELIF using a B-Twin (B-Twin ESS, Medtronic, California, USA) expandable spacer and reported a success rate of 72%. These investigators used demineralized bone matrix, cancellous allograft, or autogenous cancellous bone graft from the iliac crest and placed it into the disc space before cage insertion; there were 2 cases of nonunion. Thus, the trend in PELIF has evolved from a rigid stand-alone cage to a self-expandable cage with percutaneous pedicle screw placement.

A recent study by Wu et al.\textsuperscript{49} focused on full-endoscopic posterolateral endoscopic fusion in foraminal stenosis secondary to severe collapsed disc space. These investigators reported 30 levels of PELIF with a mean follow-up of 12 months. They reported significant pain relief and restoration of the disc height without early subsidence or exiting nerve root dysesthesia. Another recent case-control study compared the outcomes between patients undergoing open TLIF and PELIF.\textsuperscript{50} The investigators concluded that PELIF was a feasible option for single-segment lumbar degenerative diseases and was characterized by small trauma, quick recovery, and low cost. A prospective cohort study by Ao et al.

Figure 10. The timeline of evolution of percutaneous endoscopic lumbar interbody fusion (PELIF). MIS, minimally invasive surgery; TLIF; transforaminal lumbar interbody fusion.
compared the surgical outcomes between PELIF and MIS-TLIF and concluded that PELIF had less surgical trauma, less postoperative low-back pain, less hidden blood loss, and faster recovery compared with MIS-TLIF (Figure 10).32

**EVOLUTION OF T-ESS TECHNIQUES IN THE THORACIC SPINE**

Percutaneous endoscopic thoracic discectomy is a newly emerging indication in ESS. Several investigators have reported excellent to good results after percutaneous endoscopic thoracic discectomy in indications such as thoracic disc herniations, ossified posterior longitudinal ligament, and osteoporotic vertebral fractures.33-34 The anatomy and foraminal dimensions in the thoracic region are different because of the presence of rib, and a procedure of foraminal widening or foraminoplasty is required to insert the working channel. Anatomic structures such as the rib head, especially in mid and upper thoracic regions, hamper the full maneuverability of the transformaminal endoscope, which is easier in the lumbar region. Also, the incidence of epidural bleeding in this narrow space may restrict clear visualization and hamper the full use of this technique. Quillo-Olvera and Kim35 recently described a hybrid technique of rigid tubular retractors and T-ESS to approach intracanal herniated thoracic discs. These investigators described 3 cases of intracanal herniated thoracic discs managed using an oblique paraspinous approach to widen the thoracic foramen with rigid tubular retractors. The foraminal widening was followed by a new incision, lateral to the previous incision and performing a T-ESS.

**EVOLUTION OF EXTENDED INDICATIONS IN T-ESS**

Although T-ESS began with intradiscal excision of the nucleus pulposus, the indications have expanded with the advent of new approaches such as outside-in, half-and-half,36 transiliac for L5-S1 disc herniation,37 transaminar,38 contralateral,39 transpedicular, and transfacetal.40 The array of common clinical conditions that can be managed by transformaminal endoscopy is continually increasing with rapid developments, including noncontained disc herniations,40 foraminal and extraforaminal disc herniations,41,42 recurrent LDHs,43 calcified LDHs,43 foraminal stenosis requiring foraminotomy,44 lateral recess stenosis,45-48 full-endoscopic transformaminal interbody fusions,49-51 adjacent segment disease,52 highly migrated intracanal or sequestrated disc herniations,53-45 lumbar synovial cyst,56-57 acute pyogenic spondylodiscitis,58-59 thoracic spinal stenosis,60-62 osteoporotic vertebral fractures, lumbar perineural cyst,63 epidural hematoma,64 lumbar discalest,65 and lumbar aneurysmal bone cyst.66

**ENVISAGEMENT OF FUTURE DIRECTIONS OF T-ESS**

**Navigated Endoscopic Discectomy**

Navigation has established a foothold in spine MIS. The same trend seems to be the future for ESS with the advent of navigated endoscopic burrs and instruments. The future of three-dimensional (3D) navigated ESS regarding foraminotomy and interbody fusions seems promising. A recent study of the learning curve of navigation-assisted PELD suggested reduced preoperative location time, fluoroscopy time, operation time, and puncture-channel time with a definitive trajectory. The investigators concluded that navigation reshaped the learning curve of PELD for beginners and significantly decreased the learning difficulty (Figure 11).70

**O-Arm Navigation and 3D Visualization of the Anatomy**

The introduction of O-arm with navigation helps visualize the anatomy before and after decompression. Myelography performed

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Figure 11. (A) Navigation-assisted transformaminal endoscopic spine surgery, (B) O-arm navigation-assisted transformaminal endoscopic spine surgery, and (C) navigated endoscopic burr.
before the procedure shows an incomplete dye flow at the compressed level. After the decompression, the radiopaque dye flow can be visualized clearly with O-arm visualization. O-arm associated 3D navigation provides an opportunity for the use of ESS in severe cases of degenerative scoliosis with foraminal stenosis in which achieving a perfect trajectory of the working cannula and optimum resection of the superior facet is of prime importance. A recent learning curve study on O-arm—based navigation in PELD advocated its safety, accuracy, and efficiency in the treatment of LDH. The investigators concluded that the technique of O-arm—based navigation reshaped the learning curve of PELD and reduced the surgical difficulty along with radiation exposure (Figure 11).  

Navigate Endoscopic Lumbar Fusions
Navigated endoscopic lumbar interbody fusions are possible in the complicated anatomy of the disc spaces. The disc spaces can be entirely visualized with the help of the endoscope, and the extent of end-plate preparation can be almost accurately seen with the endoscope when using navigated endoscopic drills (Figure 12).

Virtual Reality and Future of T-ESS
Recently, some investigators have reported the feasibility of performing virtual reality—based presurgical planning in T-ESS. A cadaveric study by Zhou et al. compared the surgical time, radiation exposure time, and accuracy of transforminal endoscopic discectomy in 14 cadavers between the manual placement of the working cannula and virtual reality—based isocentric navigation based cannula placement. The investigators concluded that virtual reality enables precise surgical planning and has the potential for application in clinical practice. A recent systematic review of the application of virtual reality, augmented reality, and mixed reality in spine MIS and ESS concluded that the studies showed an improvement in patient outcomes and technical skills at short-term follow-up but warned that the
study quality and level of evidence remained low. Zheng et al. reported a prospective randomized trial comparing conventional and virtual reality methods for planning in 30 patients. These investigators advocated that virtual reality is an accurate planning system and significantly improves the puncture accuracy of T-ESS and reduces the fluoroscopic time.

**CONCLUSIONS**

The rapid expansion of T-ESS at the beginning of the twenty-first century can be attributed to the efforts of endoscopic surgeons of the twentieth century. So far, numerous studies have been reported under the name of transforaminal endoscopic discectomy. However, once we look over the techniques used by the investigators of the studies in detail, there are a wide variety of surgical tricks, and many technical differences, so, as experts in ESS, we wonder if it is justified to regard them as transforaminal endoscopic discectomy. Of course, we are fully aware of the importance of standardization of specific therapies or surgical methods from the perspective of evidence-based medicine. However, for better development, we should not lock the medical establishment in the trap of standardization. We speculate that education for novices should be a gift of standardization but that opportunities for disparate and disruptive trailblazers should be left open for technological advances and endless evolution.

The technique modifications from inside-out to outside-in and half-and-half have opened new horizons in the applicability of T-ESS for common clinical scenarios in the spine. The future of T-ESS is bright, with further advancements in optics, illumination, monitors, strong instruments, navigation, virtual reality, augmented reality, and mixed reality. The future of T-ESS will depend on rapid adaptations of the technological advancements in the coming decades.

**CRediT AUTHORSHIP CONTRIBUTION STATEMENT**

Ashwinkumar Vasant Khandge: Conceptualization, Writing - original draft, Writing - review & editing. Sagar Bhupendra Sharma: Conceptualization, Formal analysis, Data curation. Jin-Sung Kim: Conceptualization.

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