Review Article

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Is minimally invasive surgery a game changer in spinal surgery?

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Minimally invasive spine surgery (MISS) has revolutionized the treatment of spinal disorders over the past few decades. This review provides an in-depth analysis of MISS techniques, technologies, outcomes, and future directions. The evolution of MISS techniques–including tubular retractor systems, percutaneous pedicle screw fixation, minimally invasive transforaminal lumbar interbody fusion, lateral lumbar interbody fusion, and endoscopic spine surgery–has expanded the scope of treatable spinal pathologies while minimizing tissue trauma. Technological advancements such as intraoperative navigation, robotics, and augmented reality applications have enhanced precision and capabilities. Clinical evidence supports the efficacy and safety of MISS techniques for various spinal pathologies, demonstrating comparable or superior outcomes to traditional open approaches with reduced tissue trauma, blood loss, and hospital stays. Cost-effectiveness analyses also favor MISS over open techniques. Future directions in MISS include expanding indications, integrating artificial intelligence and machine learning, advancing tissue engineering and biologics, and refining robotic and augmented reality applications. As MISS continues to evolve, it is poised to play an increasingly important role in the treatment of spinal disorders, offering improved patient outcomes with reduced morbidity. However, ongoing rigorous evaluation of new techniques and technologies is crucial to balance potential benefits with associated risks and costs.

Keywords: Minimally invasive spine surgery; Microscopy; Endoscopy; Navigation; Augmented reality navigation

Introduction

Minimally invasive spine surgery (MISS) has revolutionized the treatment of spinal disorders over the past few decades, marking a paradigm shift in surgical approach and patient care [1,2]. The primary goals of MISS are to achieve clinical outcomes comparable to or better than traditional open surgery while minimizing tissue trauma, reducing blood loss, decreasing postoperative pain, and accelerating patient recovery [3]. Significant technological and technical advancements have made these objectives increasingly attainable, expanding the scope of MISS to address a wide range of spinal pathologies, including degenerative disc disease, spinal stenosis, herniated discs, spondylolisthesis, spinal deformities, trauma, and tumors. This comprehensive review provides an in-depth analysis of the MISS techniques, technologies, outcomes, and future directions, highlighting its evolution from its inception to its current state and beyond.

Historical Development and Evolution of Minimally Invasive Spine Surgery Techniques

The origins of MISS date back to the 1970s, with the introduction of chemonucleolysis for treating lumbar disc herniation. However, the 1990s heralded the modern era of MISS, driven by the development of tubular retractor systems and the integration of endoscopic techniques into spine surgery. This section describes the key milestones that have shaped the field of MISS.

Tubular retractor systems

The introduction of tubular retractors in the late 1990s marked a significant advancement in MISS. The METRx system, introduced in 1997, enabled surgeons to perform microdiscectomies through a muscle-splitting approach, minimizing tissue disruption while maintaining adequate visualization [4]. This technology paved the way for a variety of tubular-based procedures, including microdecompression for spinal stenosis and minimally invasive transforaminal lumbar interbody fusion (MI-TLIF) [5].

The advantages of tubular approaches are well-documented. A meta-analysis by Goldstein et al. [6] comparing tubular microdiscectomy to open microdiscectomy found comparable clinical outcomes with significantly less surgical site pain and shorter length of hospital stay in the tubular group. Several subsequent studies have corroborated these findings, establishing tubular techniques as a cornerstone of MISS.

The tubular systems have continued to evolve, with significant advances in design and functionality. The development of expandable retractors and specialized instruments has helped optimize procedures through these narrow corridors. Recent advancements include integrated light sources and suction capabilities, further enhancing intraoperative visual access and efficiency.

Percutaneous pedicle screw fixation

Percutaneous pedicle screw fixation, introduced in the early 2000s, marked a significant milestone in minimally invasive spinal stabilization [7]. This technique enables surgeons to place pedicle screws through small stab incisions, avoiding the extensive muscle dissection required in traditional open approaches.

A systematic review and meta-analysis by Phan et al. [8] compared percutaneous and open pedicle screw fixation in 1,028 patients. The results demonstrated significantly lower blood loss and shorter hospital stays in the percutaneous group, with no significant difference in operative time or complication rates [8]. These findings underscore the potential benefits of percutaneous techniques in reducing surgical morbidity.

The accuracy of percutaneous pedicle screw placement has been extensively investigated. A meta-analysis by Perdomo-Pantoja et al. [7] analyzing 48,757 percutaneously placed pedicle screws reported an overall accuracy rate of 93.3%, a figure comparable to traditional open techniques. The integration of navigation and robotic systems has further improved the accuracy of percutaneous screw placement, with some studies reporting accuracy rates exceeding 98%.

Minimally invasive transforaminal lumbar interbody fusion

MI-TLIF has emerged as a leading MISS technique since its introduction in the mid-2000s. This versatile approach effectively treats various lumbar pathologies, including degenerative disc disease, spondylolisthesis, and recurrent disc herniation [9]. This technique combines the principles of minimally invasive decompression, interbody fusion, and percutaneous pedicle screw fixation (Fig. 1).

A comprehensive meta-analysis by Hu et al. comparing MI-TLIF to open TLIF found that MI-TLIF was associated with significantly less blood loss, shorter hospital stays, and lower complication rates [10]. Importantly, there were no significant differences in terms of operative time, fusion rates, or clinical outcomes between the two techniques.

The long-term outcomes of MI-TLIF have also been encouraging. A prospective study by Adogwa et al. [9] enrolling 148 patients undergoing MI-TLIF found sustained improvements in back pain, leg pain, and disability, with a fusion rate of 96% at 5 years. These results suggest sustained benefits of MI-TLIF over time. Recent advancements in MI-TLIF techniques include the use of expandable interbody cages, which allow the insertion of larger implants through small working channels, potentially improving lordosis restoration and indirect decompression [11].

Lateral lumbar interbody fusion

Developed in the late 2000s, lateral lumbar interbody fusion (LLIF) techniques, including extreme lateral interbody fusion and oblique lateral interbody fusion

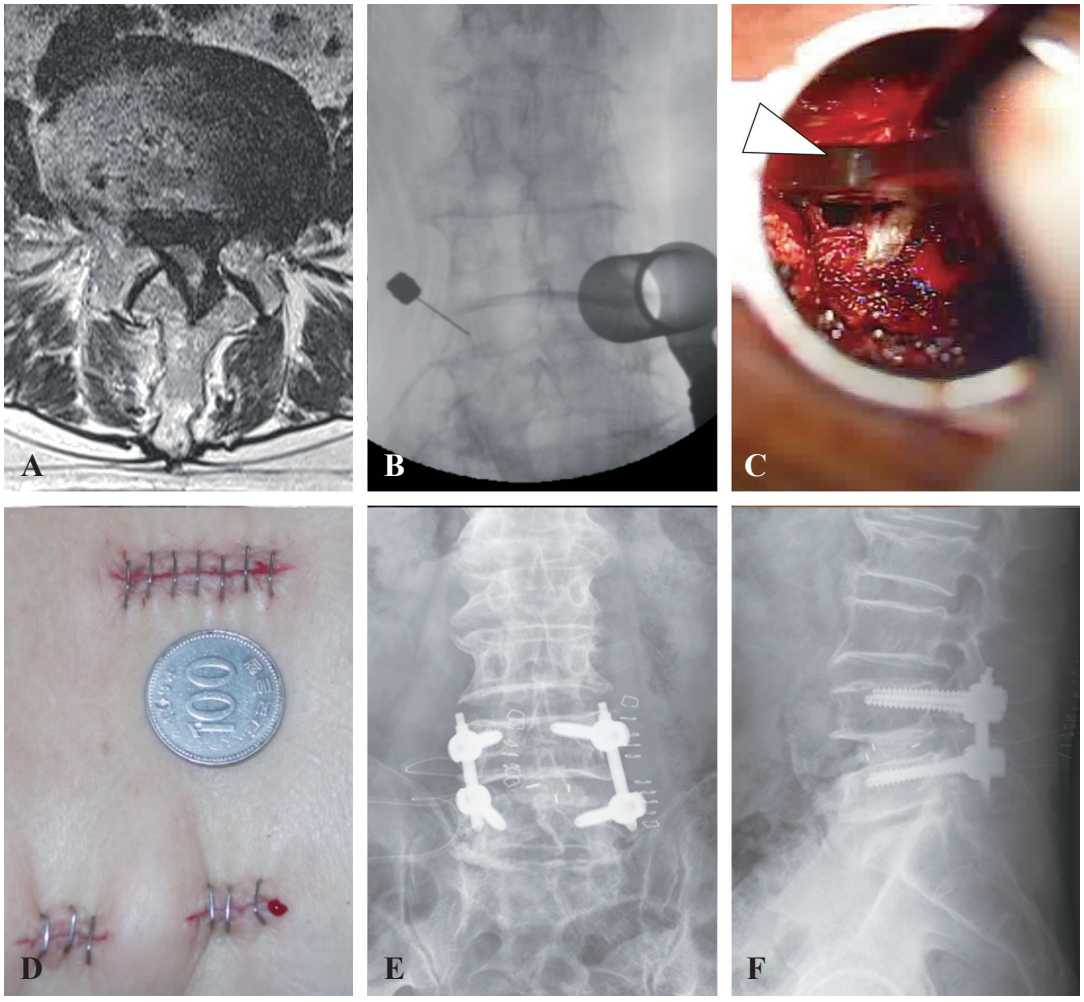

Fig. 1. (A) Severe central stenosis observed in a 65-year-old male patient. **(B)** Intraoperative C-arm images after positioning the tubular retractor. **(C)** Intraoperative microscopic image showing endplate preparation using a reamer (white arrowhead). **(D)** Three small incisions visible: the right-side incision for the tubular retractor and two for percutaneous screw insertion. **(E, F)** Postoperative anteroposterior and lateral radiographs demonstrating well-positioned interbody cage and four percutaneous pedicle screws.

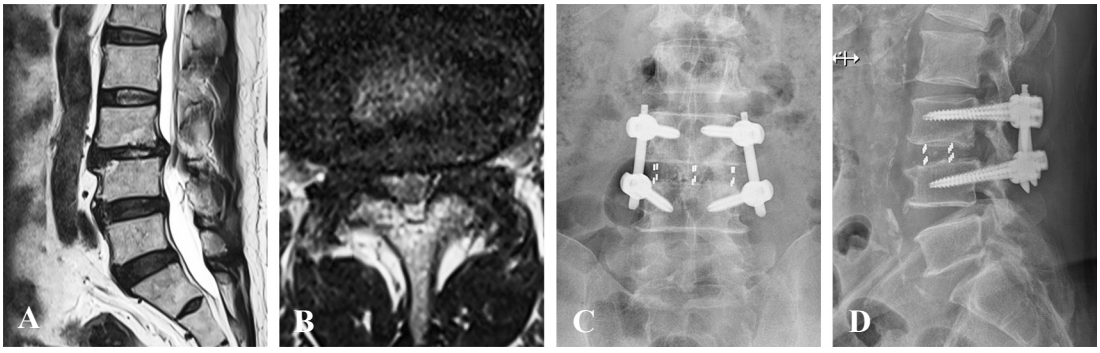

Fig. 2. Lateral lumbar interbody fusion in a 62-year-old male patient. **(A, B)** Severe central stenosis with mild spondylolisthesis and centrally herniated disc observed preoperatively. **(C, D)** Lateral interbody fusion with percutaneous screw fixation, showing significantly restored intervertebral disc height.

(OLIF), provide an alternative approach to interbody fusion [12]. These techniques entail gaining access to the disc space through a retroperitoneal approach, avoiding disruption of the posterior musculature and facet joints (Fig. 2).

A systematic review by Hijji et al. [12] analyzing

6,819 patients undergoing LLIF found high fusion rates and significant improvements in patient-reported outcomes, with a relatively low overall complication rate. The most common complications were transient thigh symptoms (36.07%), which typically resolved within 6 months postoperatively [13].

LLIF techniques have been particularly useful in treating adult spinal deformity and multi-level degenerative disc disease. A multicenter study by Berjano et al. [14] involving 12 patients undergoing LLIF for adult spinal deformity reported significant improvements in coronal Cobb angle and sagittal vertical axis. The study concluded that LLIF, when combined with posterior percutaneous fixation, can achieve meaningful deformity correction with reduced morbidity compared to traditional open techniques. Recent innovations in LLIF include the development of navigation-assisted techniques and specialized retractor systems designed to minimize the risk of neural complications [15].

Endoscopic spine surgery

The most recent advancement in MISS is the emergence of endoscopic techniques, which have gained widespread acceptance since the 2010s. These cutting-edge procedures are performed through a single small incision using specialized endoscopes with working channels, allowing for decompression and discectomy under continuous visual access [16].

A meta-analysis by Shi et al. [17] comparing full-endoscopic to microendoscopic discectomy found comparable clinical outcomes with significantly shorter operative time and hospital stay in the full-endoscopic group. These findings suggest that full-endoscopic techniques may offer advantages in terms of surgical efficiency and recovery time. The applications of full-endoscopic spine surgery have expanded beyond simple discectomies to include more complex procedures such as foraminotomy, central canal decompression, and even interbody fusion [18]. One of the main challenges associated with full-endoscopic techniques is the steep learning curve. The importance of structured training programs and proctorship to ensure the safe adoption of these techniques has been emphasized [19].

Technological Advancements in Minimally Invasive Spine Surgery

The progress in MISS has been largely driven by technological innovations that have enhanced visualization, improved accuracy, and expanded the capabilities of minimally invasive techniques. This section explores key technological advancements that have shaped the field of MISS.

Intraoperative navigation

Intraoperative navigation systems have transformed the landscape of MISS, particularly in the realm of pedicle screw placement. By seamlessly integrating preoperative or intraoperative imaging with real-time instrument tracking, these advanced systems provide surgeons with unparalleled precision, enhanced accuracy, and improved safety.

A meta-analysis by Tian et al. [20] demonstrated the superiority of navigation-assisted pedicle screw placement over freehand techniques in terms of improved screw placement accuracy and reduced risk of cortical perforation. This improved accuracy translates to enhanced patient safety and potentially reduced reoperation rates for screw malposition.

Robotics

Robotic assistance in spine surgery represents a natural evolution of navigation technology, aiming to enhance the precision and consistency of procedures [21]. While still in its early stages, robotic spine surgery shows promise in improving accuracy and potentially reducing complications. Moreover, the integration of robotic assistance with navigation systems can potentially mitigate concerns related to distorted anatomical landmarks, thereby enhancing the overall surgical outcomes [22] (Fig. 3).

Robotic assistance has been highlighted as a valuable tool for pedicle screw placement in LLIF procedures.

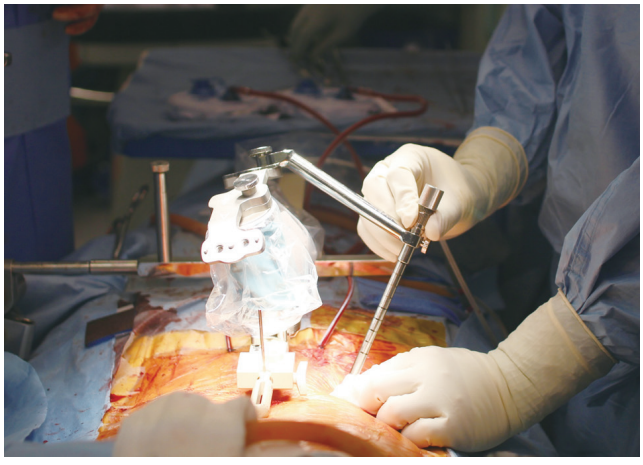

Fig. 3. Robot-assisted pedicle screw fixation.

Studies have shown that robotic-guided pedicle screw placement can increase accuracy, reduce operative time, and decrease radiation exposure, making it particularly advantageous in MISS [15].

Augmented reality

Augmented reality (AR) systems represent the cutting edge of visualization technology in spine surgery. By overlaying computer-generated images onto the surgeon's view of the operative field, AR enables real-time, three-dimensional (3D) visualization of patient anatomy and surgical instrumentation [23,24] (Fig. 4).

Initial studies on AR in spine surgery have demonstrated its potential for improving pedicle screw placement accuracy. A pilot study by Elmi-Terander et al. [25] using an AR surgical navigation system for thoracic pedicle screw placement achieved an accuracy rate of 94.1%, comparable to conventional navigation systems. The AR system enabled continuous visualization of the screw trajectory without diverting gaze from the surgical field, potentially improving workflow efficiency. A feasibility study by Müller et al. [26] using a head-mounted AR display for pedicle screw fixation achieved accuracy comparable to the gold standard of high-end pose-tracking systems.

Clinical Outcomes and Evidence

The efficacy and safety of MISS techniques have been extensively studied over the past 2 decades. This section provides a comprehensive overview of the current evidence supporting the use of MISS for various spinal pathologies.

Decompression procedures

Minimally invasive decompression techniques, including tubular discectomy and endoscopic decompression, have been widely adopted for the treatment of lumbar disc herniation and spinal stenosis. A Cochrane review by Overdevest et al. [27] analyzed data from 10 randomized controlled trials comparing minimally invasive to open decompression for lumbar spinal stenosis. The authors found no significant differences between the two techniques in terms of leg pain, disability, or walking ability at long-term follow-up. However, minimally invasive techniques were associated with less low back pain in the short term and shorter hospital stays [27]. For lumbar disc herniation, a meta-analysis by Ruan et al. [28] comparing percutaneous endoscopic lumbar discectomy to open microdiscectomy found comparable rates of postoperative back pain, complications, reoperation, and Oswestry Disability Index (ODI).

Recent clinical studies have consistently demonstrated the efficacy of biportal endoscopic lumbar discectomy in treating lumbar disc herniation. In a multicenter, retrospective study, the clinical outcomes of biportal endoscopic discectomy were similar to those of open microscopic discectomy, with benefits such as minimal estimated blood loss, shorter hospital stay, and reduced early postoperative back pain [29,30]. Moreover, biportal endoscopic lumbar discectomy has also shown promising results in obese individuals, highlighting its potential as a viable treatment option for this specific patient population [31,32]. Furthermore, biportal endoscopic laminectomy has been shown to be a satisfactory option for patients with lumbar spinal stenosis, offering favorable clinical outcomes and potentially improving postoperative recovery [33-38].

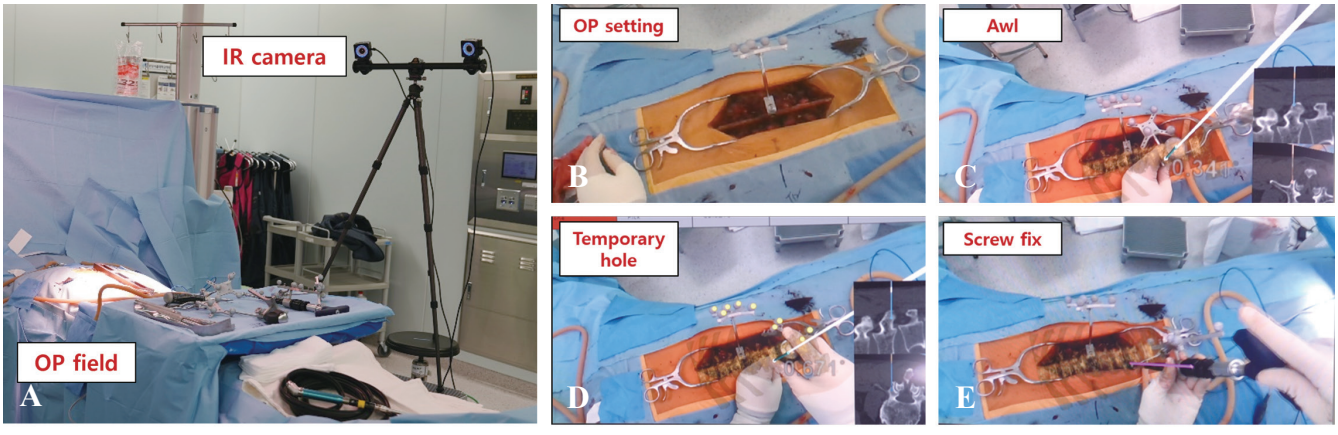

Fig. 4. (A–E) Augmented reality-assisted spine surgery. OP field, operative field; IR, infrared camera.

Fusion procedures

Minimally invasive fusion techniques, particularly MI-TLIF, LLIF, and endoscopic lumbar interbody fusion (LIF) have become increasingly popular for treating various lumbar pathologies requiring arthrodesis. A network meta-analysis by Lu et al. [39] comparing various LIF techniques found that MISS was associated with the lowest risk of surgical site infection and the shortest hospital stay compared to open techniques, while clinical outcomes, including improvements in pain and disability scores, remained comparable across techniques. In a recent meta-analysis by Zhang et al. [40], the OLIF group showed more significant improvement in Visual Analog Scale (VAS) score for radiating pain, while the improvements in VAS score for back pain and the ODI scores were comparable. OLIF was associated with a significantly shorter duration of surgery and less intraoperative blood loss than minimally invasive surgery (MIS)-TLIF, even with supplementary posterior fixations.

Full-endoscopic LIF demonstrated promising initial results, outperforming MIS-TLIF in terms of blood loss and VAS score for back pain [41]. However, no significant differences were observed between the two techniques in terms of complications, short- or medium-term clinical outcomes, and fusion rates. The clinical and radiographic outcomes of biportal endoscopic LIF were comparable to those of MIS-TLIF [42] (Fig. 5).

Deformity correction

MISS techniques for adult spinal deformity correction have been an area of significant interest and innovation in recent years [43]. Recent studies demonstrate that MISS techniques reduce overall complication rates associated with deformity correction surgeries [44]. While open surgery remains the gold standard, MISS has shown satisfactory clinical outcomes for deformity correction. Furthermore, minimally invasive approach-

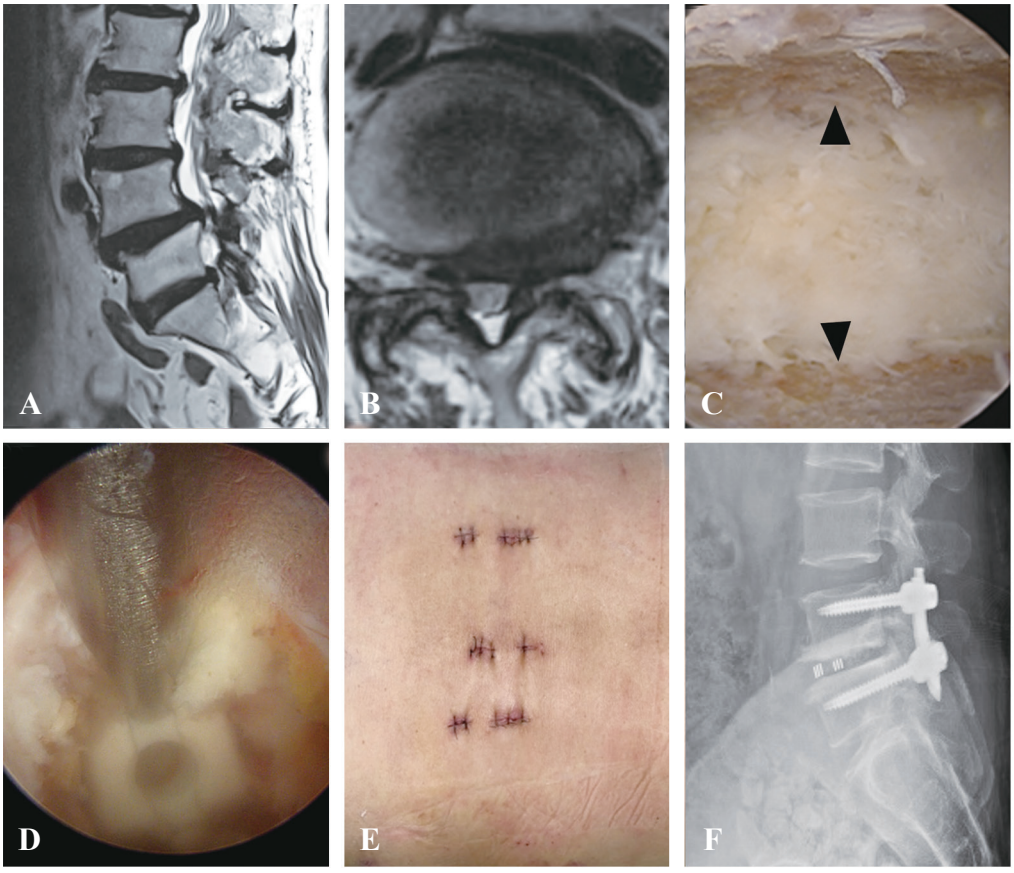

Fig. 5. (A, B) Patient with severe central stenosis and grade 1 spondylolisthesis at L4–5 undergoing biportal endoscopic transforaminal interbody fusion. **(C)** Biportal endoscopic approach providing clear visualization of endplate preparation, enabling complete preparation (black arrowhead). **(D)** Safe cage insertion achieved under endoscopic guidance. **(E)** Six small incisions visible: two for endoscope access and four for percutaneous screw insertion. **(F)** Postoperative lateral lumbar radiograph showing anteriorly positioned lumbar cage and four inserted pedicle screws.

es using long spinal constructs have been explored for assessing fractures, tumors, or deformities, particularly in elderly or debilitated patients [45]. The concept of a triad of MIS procedures for adult spinal deformity (ASD) includes anterior column realignment, LLIF, and percutaneous pedicle screw fixation. This combination is suggested to reduce the number of fusion segments required for normalizing spinopelvic mismatch while providing indirect neural decompression [46].

Cost-effectiveness

The economic impact of MISS has garnered significant attention amidst rising healthcare costs and the emphasis on value-based care. Research has shown that MISS procedures can offer substantial cost savings. For example, a comparative analysis of MI-TLIF and open TLIF revealed that higher implant costs of ML-TILF were offset by lower overall hospital costs, driven by shorter lengths of stay and reduced complication rates [47]. When factoring in societal costs, such as earlier return to work, the cost savings associated with MI-TLIF were even more pronounced. Additional studies have highlighted the cost disparity between open and MI-TILF, with open TLIF incurring significantly higher costs–averaging US$ 4,038–compared to MI-TLIF [48]. In the realm of lumbar discectomy surgeries, endoscopic procedures, such as full-endoscopic and biportal endoscopic discectomy, have proven more cost-effective than microscopic discectomy [49].

Future Directions

An exciting development is the expansion of indications for MISS techniques. Researchers are now investigating the use of minimally invasive approaches for more complex spinal pathologies, including ASD, high-grade spondylolisthesis, and spinal tumors [1]. Recent studies suggest that carefully designed minimally invasive approaches may achieve outcomes comparable to traditional open techniques, while potentially reducing morbidity and improving recovery times.

The incorporation of advanced imaging and navigation technologies represents another area of rapid development in MISS. The integration of intraoperative CT, 3D fluoroscopy, and electromagnetic navigation systems is poised to enhance the precision and safety of MISS procedures [50]. Furthermore, the emerging application of machine learning algorithms in navigation systems promises to revolutionize surgical planning. By analyzing patient-specific anatomy, these algorithms can potentially predict optimal screw placement trajectories, further improving surgical accuracy and safety.

Artificial intelligence (AI) and machine learning applications in MISS extend beyond navigation systems. These technologies are being leveraged for preoperative planning, intraoperative guidance, and outcome prediction, revolutionizing the surgical landscape. AI-powered systems for automated surgical planning for complex procedures show promise in streamlining the planning process and improving consistency. Machine learning algorithms are also being developed to predict patient outcomes, potentially assisting in patient selec-

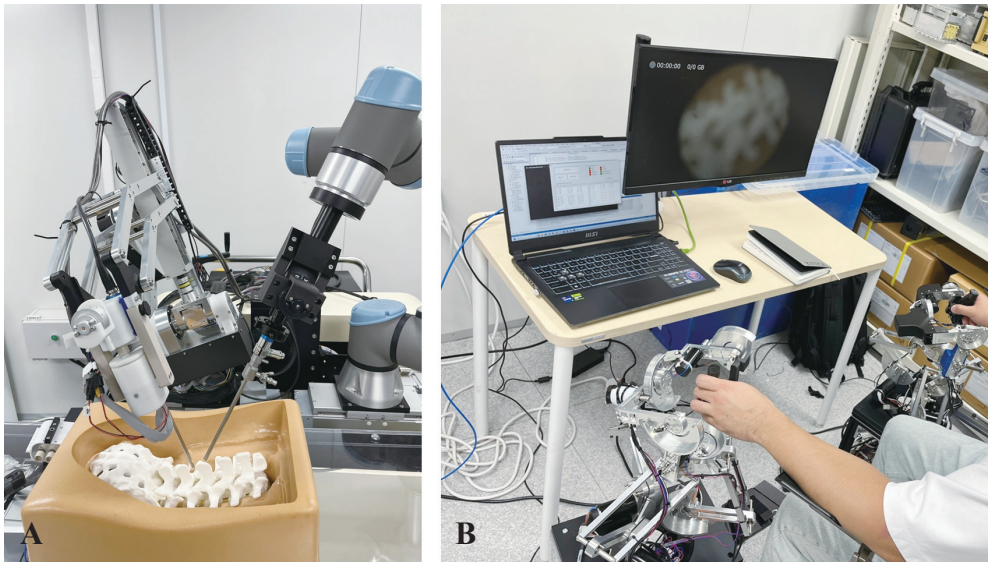

Fig. 6. (A, B) Robot-assisted biportal endoscopy system.

tion and informed decision-making [51].

Advancements in tissue engineering and biologics represent another exciting frontier in MISS. Researchers are developing novel synthetic bone graft substitutes and exploring the use of 3D-printed biodegradable scaffolds seeded with mesenchymal stem cells for interbody fusion. These innovations aim to enhance fusion rates and accelerate healing in MISS procedures, potentially improving long-term outcomes of minimally invasive fusion procedures.

The integration of robotics with endoscopic spine surgery is an exciting development in MISS. Robotic systems are being designed to enable precise control of endoscopes and instruments during minimally invasive procedures, potentially enhancing accuracy and reducing the learning curve associated with these techniques (Fig. 6).

Finally, AR technology is being explored as a tool for surgical education and training in MISS. AR systems can overlay computer-generated images onto the surgeon's view of the operative field, providing real-time, 3D visualization of patient anatomy [24]. In surgical education, AR-assisted training programs show significant potential in helping trainees achieve proficiency in complex minimally invasive techniques more quickly than traditional methods.

Conclusions

Minimally invasive spine surgery has made remarkable strides since its inception, evolving from simple discectomy surgery to complex deformity corrections. A growing body of evidence supports the efficacy and safety of MISS techniques for a wide range of spinal pathologies, demonstrating comparable or superior outcomes to traditional open approaches with the added benefits of reduced tissue trauma, less blood loss, shorter hospital stays, and faster recovery.

The integration of advanced technologies such as navigation systems, robotics, and AR has further enhanced the capabilities of MISS, improving accuracy and potentially expanding the scope of treatable conditions. As these technologies continue to evolve and new biological solutions emerge, the field of MISS is poised for continued growth and innovation.

As the healthcare landscape evolves, MISS is likely to play an increasingly important role in the treatment of spinal disorders. The growing preference for less invasive interventions, coupled with an aging population and increasing demand for faster recovery and expedited return to functionality, will continue to drive innovation in this field. Moving forward, rigorous evaluation of new techniques and technologies will be essential, carefully weighing potential benefits against associated risks and costs.

In conclusion, MISS represents a paradigm shift in the treatment of spinal disorders, promising improved patient outcomes with reduced morbidity. As the field continues to evolve, interdisciplinary collaboration between surgeons, engineers, and researchers will be essential to realize the full potential of MISS and ultimately improve the lives of patients with spinal pathologies.

Key Points

- Minimally invasive spine surgery (MISS) techniques have evolved to address a wide range of spinal pathologies, offering comparable or superior outcomes to traditional open approaches with reduced tissue trauma and faster recovery.
- Technological advancements such as intraoperative navigation, robotics, and augmented reality have significantly enhanced the precision and capabilities of MISS procedures.
- Clinical evidence supports the efficacy, safety, and cost-effectiveness of MISS for various spinal conditions, including decompression, fusion, and deformity correction.
- The integration of artificial intelligence, machine learning, and advanced biologics promises to further improve surgical planning, execution, and outcomes in MISS.

Conflict of Interest

Sang-Min Park and Ho-Joong Kim serve as Editorial Board members of the *Asian Spine Journal* but have no role in the decision to publish this article. Except for that, no potential conflict of interest relevant to this article was reported.

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Author Contributions

SMP is first author who carried out the literature survey

and wrote the manuscript; SMP, HJK, JSY participated in the design and had primary responsibility for the final manuscript and helped to revise the manuscript; all authors read and approved the final manuscript.

References

1. Choi JY, Park SM, Kim HJ, Yeom JS. Recent updates on minimally invasive spine surgery: techniques, technologies, and indications. Asian Spine J 2022;16:1013-21.
2. Park J, Ham DW, Kwon BT, Park SM, Kim HJ, Yeom JS. Minimally invasive spine surgery: techniques, technologies, and indications. Asian Spine J 2020;14:694-701.
3. Goldberg JL, Hartl R, Elowitz E. Minimally invasive spine surgery: an overview. World Neurosurg 2022;163:214-27.
4. Foley KT, Smith MM, Rampersaud YR. Microendoscopic approach to far-lateral lumbar disc herniation. Neurosurg Focus 1999;7:e5.
5. Boukebir MA, Berlin CD, Navarro-Ramirez R, et al. Ten-step minimally invasive spine lumbar decompression and dural repair through tubular retractors. Oper Neurosurg (Hagerstown) 2017;13:232-45.
6. Goldstein CL, Macwan K, Sundararajan K, Rampersaud YR. Perioperative outcomes and adverse events of minimally invasive versus open posterior lumbar fusion: meta-analysis and systematic review. J Neurosurg Spine 2016;24:416-27.
7. Perdomo-Pantoja A, Ishida W, Zygourakis C, et al. Accuracy of current techniques for placement of pedicle screws in the spine: a comprehensive systematic review and meta-analysis of 51,161 screws. World Neurosurg 2019;126:664-78.
8. Phan K, Rao PJ, Mobbs RJ. Percutaneous versus open pedicle screw fixation for treatment of thoracolumbar fractures: systematic review and meta-analysis of comparative studies. Clin Neurol Neurosurg 2015;135:85-92.
9. Adogwa O, Parker SL, Bydon A, Cheng J, McGirt MJ. Comparative effectiveness of minimally invasive versus open transforaminal lumbar interbody fusion: 2-year assessment of narcotic use, return to work, disability, and quality of life. J Spinal Disord Tech 2011;24:479-84.
10. Hu X, Yan L, Jin X, Liu H, Chai J, Zhao B. Endoscopic lumbar interbody fusion, minimally invasive transforaminal lumbar interbody fusion, and open transforaminal lumbar interbody fusion for the treatment of lumbar degenerative diseases: a systematic review and network meta-analysis. Global Spine J 2024;14:295-305.
11. Kim CW, Doerr TM, Luna IY, et al. Minimally invasive transforaminal lumbar interbody fusion using expandable technology: a clinical and radiographic analysis of 50 patients. World Neurosurg 2016;90:228-235.
12. Hijji FY, Narain AS, Bohl DD, et al. Lateral lumbar interbody fusion: a systematic review of complication rates. Spine J 2017;17:1412-9.
13. Chang SY, Lee WS, Mok S, Park SC, Kim H, Chang BS. Anterior thigh pain following minimally invasive oblique lateral interbody fusion: multivariate analysis from a prospective case series. Clin Orthop Surg 2022;14:401-9.
14. Berjano P, Cecchinato R, Sinigaglia A, et al. Anterior column realignment from a lateral approach for the treatment of severe sagittal imbalance: a retrospective radiographic study. Eur Spine J 2015;24 Suppl 3:433-8.
15. Huntsman KT, Riggleman JR, Ahrendtsen LA, Ledonio CG. Navigated robot-guided pedicle screws placed successfully in single-position lateral lumbar interbody fusion. J Robot Surg 2020;14:643-7.
16. Kim JS, Bae J, Lee DC, et al. Evaluation of the efficacy and safety of conventional and interlaminar full-endoscopic decompressive laminectomy to treat lumbar spinal stenosis (ENDO-F trial): protocol for a prospective, randomized, multicenter trial. PLoS One 2023;18:e0283924.
17. Shi R, Wang F, Hong X, et al. Comparison of percutaneous endoscopic lumbar discectomy versus microendoscopic discectomy for the treatment of lumbar disc herniation: a meta-analysis. Int Orthop 2019;43:923-37.
18. Wu PH, Kim HS, Jang IT. A narrative review of development of full-endoscopic lumbar spine surgery. Neurospine 2020;17(Suppl 1):S20-33.
19. Gadjradj PS, Vreeling A, Depauw PR, Schutte PJ, Harhangi BS; PTED-Study Group. Surgeons learning curve of transforaminal endoscopic discectomy for sciatica. Neurospine 2022;19:594-602.
20. Tian NF, Huang QS, Zhou P, et al. Pedicle screw insertion accuracy with different assisted methods: a systematic review and meta-analysis of comparative studies. Eur Spine J 2011;20:846-59.
21. Park SM, Kim HJ, Lee SY, Chang BS, Lee CK, Yeom JS. Radiographic and clinical outcomes of robot-assisted posterior pedicle screw fixation: two-year results from a randomized controlled trial. Yonsei Med J 2018;59:438-44.
22. Fayed I, Tai A, Triano MJ, et al. Lateral versus prone robot-assisted percutaneous pedicle screw placement: a CT-based comparative assessment of accuracy. J Neurosurg Spine 2022;37:112-20.
23. Pierzchajlo N, Stevenson TC, Huynh H, et al. Augmented reality in minimally invasive spinal surgery: a narrative review of available technology. World Neurosurg 2023;176:35-42.
24. Park SM, Kim HJ, Yeom JS, Shin YG. Spine surgery using augmented reality. J Korean Soc Spine Surg 2019;26:26-32.
25. Elmi-Terander A, Nachabe R, Skulason H, et al. Feasibility and accuracy of thoracolumbar minimally invasive pedicle screw placement with augmented reality navigation technology. Spine (Phila Pa 1976) 2018;43:1018-23.
26. Muller F, Roner S, Liebmann F, Spirig JM, Furnstahl P, Farshad M. Augmented reality navigation for spinal pedicle screw instrumentation using intraoperative 3D imaging. Spine J 2020;20:621-8.
27. Overdevest GM, Jacobs W, Vleggeert-Lankamp C, Thome C, Gunzburg R, Peul W. Effectiveness of posterior decompression techniques compared with conventional lami-

nectomy for lumbar stenosis. Cochrane Database Syst Rev 2015;(3):CD010036.
28. Ruan W, Feng F, Liu Z, Xie J, Cai L, Ping A. Comparison of percutaneous endoscopic lumbar discectomy versus open lumbar microdiscectomy for lumbar disc herniation: a meta-analysis. Int J Surg 2016;31:86-92.
29. Park SM, Lee HJ, Park HJ, et al. Biportal endoscopic versus microscopic discectomy for lumbar herniated disc: a randomized controlled trial. Spine J 2023;23:18-26.
30. Park SM, Song KS, Kim HJ, et al. Comparing the efficacy and safety of minimally invasive biportal endoscopic spine surgery versus conventional microscopic discectomy in single-level lumbar herniated intervertebral disc (ENDO-BH Trial): a multicenter, prospective, randomized controlled equivalence trial study protocol. Trials 2022;23:172.
31. Park HJ, Choi JY, You KH, et al. Clinical and radiologic outcomes of biportal endoscopic lumbar discectomy in obese patients: a retrospective case-control study. BMC Musculoskelet Disord 2022;23:1117.
32. Choi JY, Park HJ, Park SM, et al. Biportal endoscopic discectomy versus tubular microscopic discectomy for treating single-level lumbar disc herniation in obese patients: a multicenter, retrospective analysis. Acta Neurochir (Wien) 2023;165:2641-50.
33. Park HJ, Park SM, Song KS, et al. Evaluation of the efficacy and safety of conventional and biportal endoscopic decompressive laminectomy in patients with lumbar spinal stenosis (ENDO-B trial): a protocol for a prospective, randomized, assessor-blind, multicenter trial. BMC Musculoskelet Disord 2021;22:1056.
34. Park SM, Kim GU, Kim HJ, et al. Is the use of a unilateral biportal endoscopic approach associated with rapid recovery after lumbar decompressive laminectomy?: a preliminary analysis of a prospective randomized controlled trial. World Neurosurg 2019;128:e709-18.
35. Park SM, Kim HJ, Kim GU, et al. Learning curve for lumbar decompressive laminectomy in biportal endoscopic spinal surgery using the cumulative summation test for learning curve. World Neurosurg 2019;122:e1007-13.
36. Park SM, Park J, Jang HS, et al. Biportal endoscopic versus microscopic lumbar decompressive laminectomy in patients with spinal stenosis: a randomized controlled trial. Spine J 2020;20:156-65.
37. Junjie L, Jiheng Y, Jun L, Haixiong L, Haifeng Y. Comparison of unilateral biportal endoscopy decompression and microscopic decompression effectiveness in lumbar spinal stenosis treatment: a systematic review and meta-analysis. Asian Spine J 2023;17:418-30.
38. Park J, Ahn DK, Choi DJ. Treatment concept and technical considerations of biportal endoscopic spine surgery for lumbar spinal stenosis. Asian Spine J 2024;18:301-23.
39. Lu VM, Kerezoudis P, Gilder HE, McCutcheon BA, Phan K, Bydon M. Minimally invasive surgery versus open surgery spinal fusion for spondylolisthesis: a systematic review and meta-analysis. Spine (Phila Pa 1976) 2017;42:E177-85.
40. Zhang QY, Tan J, Huang K, Xie HQ. Minimally invasive transforaminal lumbar interbody fusion versus oblique lateral interbody fusion for lumbar degenerative disease: a meta-analysis. BMC Musculoskelet Disord 2021;22:802.
41. Chen H, Zheng G, Bian Z, et al. Comparison of minimally invasive transforaminal lumbar interbody fusion and endoscopic lumbar interbody fusion for lumbar degenerative diseases: a retrospective observational study. J Orthop Surg Res 2023;18:389.
42. Kang MS, You KH, Choi JY, Heo DH, Chung HJ, Park HJ. Minimally invasive transforaminal lumbar interbody fusion using the biportal endoscopic techniques versus microscopic tubular technique. Spine J 2021;21:2066-77.
43. Kim SW. Latest knowledge on a comprehensive understanding of cervical deformity and selection of effective treatment methods using recent classification systems: a narrative review. Asian Spine J 2024;18:608-20.
44. Eastlack RK, Srinivas R, Mundis GM, et al. Early and late reoperation rates with various MIS techniques for adult spinal deformity correction. Global Spine J 2019;9:41-7.
45. Roldan H, Perez-Orribo L, Spreafico M, Ginoves-Sierra M. Long constructs in the thoracic and lumbar spine with a minimally invasive technique. Minim Invasive Neurosurg 2011;54:100-3.
46. Tani Y, Saito T, Taniguchi S, et al. Radiographic and MRI evidence of indirect neural decompression after the anterior column realignment procedure for adult spinal deformity. J Neurosurg Spine 2022;37:703-12.
47. Vertuani S, Nilsson J, Borgman B, et al. A cost-effectiveness analysis of minimally invasive versus open surgery techniques for lumbar spinal fusion in Italy and the United Kingdom. Value Health 2015;18:810-6.
48. Lee LY, Idris Z, Beng TB, et al. Outcomes of minimally invasive surgery compared to open posterior lumbar instrumentation and fusion. Asian J Neurosurg 2017;12:620-37.
49. Choi KC, Shim HK, Kim JS, et al. Cost-effectiveness of microdiscectomy versus endoscopic discectomy for lumbar disc herniation. Spine J 2019;19:1162-9.
50. Van Berkel B, Smets G, Van Schelverghem G, et al. Comparison of radiation exposure of AIRO intraoperative CT with C-arm fluoroscopy during posterior lumbar interbody fusion. Appl Sci 2021;11:10326.
51. Yun K, Oh J, Hong TH, Kim EY. Prediction of mortality in surgical intensive care unit patients using machine learning algorithms. Front Med (Lausanne) 2021;8:621861.