Review Article

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Overview of minimally invasive nerve root decompression compared to traditional microdiscectomy and foraminotomy techniques: present and future of spinal microsurgery

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Abstract

Minimally invasive spinal surgery has revolutionized the management of degenerative spine conditions, offering solutions with reduced tissue disruption and quicker recovery compared to traditional approaches. This article provides a comprehensive analysis of minimally invasive nerve root decompression techniques, focusing on transforaminal endoscopic lumbar discectomy (TELD), and contrasts these with traditional microdiscectomy and foraminotomy. TELD's integration of advanced visualization, reduced surgical morbidity, and enhanced patient outcomes highlights its transformative impact. The review also explores innovations in biological therapies, such as platelet-rich plasma (PRP), which improve tissue healing and reduce recurrence rates. Technical refinements, patient-centered care protocols, and emerging technologies, including robotic assistance and augmented reality, further expand the scope of minimally invasive approaches. Addressing the challenges of training, cost, and patient selection, this discussion underscores TELD's potential to set new benchmarks in spinal microsurgery. The article concludes by charting future directions in regenerative medicine and personalized spinal care, reinforcing the role of minimally invasive techniques in advancing patient outcomes and healthcare efficiency.

Introduction

Spinal microsurgery has experienced significant advancements over the past few decades, revolutionizing the management of degenerative spine conditions. These advancements have been driven by the growing need for safer, less invasive, and more effective treatments for patients suffering from debilitating spinal disorders. The traditional approaches, while effective, often come with significant drawbacks, including extensive tissue disruption, prolonged recovery times, and higher complication rates. This has paved the way for the development of minimally invasive techniques (MIS), which have transformed the field of spinal surgery.[1–4]

Among the most notable MIS advancements is the transforaminal endoscopic lumbar discectomy (TELD). This technique has gained prominence due to its ability to address nerve root compression with significantly reduced surgical morbidity. TELD represents a key innovation that combines advanced visualization tools, refined surgical techniques, and the integration of biologically active substances to improve outcomes.[5–8] Unlike traditional open procedures, TELD minimizes tissue trauma while delivering comparable or superior clinical results, making it a valuable option for a growing number of patients.[9,10]

Furthermore, the shift toward minimally invasive approaches aligns with broader trends in medicine, such as enhanced recovery after surgery (ERAS) protocols, patient-centered care, and the integration of advanced technologies like robotics and augmented reality.[11,12] These advancements underscore the potential for continuous improvement in the field, promising not only better patient outcomes but also more efficient use of healthcare resources.

This article provides a comprehensive analysis of minimally invasive nerve root decompression techniques, with a focus on TELD. It contrasts these techniques with traditional surgical methods, highlighting their respective advantages and limitations, and explores the exciting future directions in spinal microsurgery. By examining the clinical evidence, technical aspects, and innovative trends shaping the field, this discussion aims to provide a thorough understanding of the evolving landscape of spinal surgery.

Traditional techniques: microdiscectomy and foraminotomy

Traditional open microdiscectomy and foraminotomy have long been the gold standards for treating lumbar disc herniation and foraminal stenosis. These techniques involve a midline or paramedian incision, muscle dissection, and direct visualization of the spinal canal and nerve roots to remove herniated disc material or decompress stenotic foramina.[4,13]

Advantages

i. **Proven efficacy:** Long-term follow-up studies consistently show relief of radicular symptoms and improved functional outcomes. These procedures are well-documented in medical literature, providing a robust body of evidence supporting their use.[1,4]

ii. **Direct access:** The surgical field allows for clear visualization of neural and disc structures, enabling surgeons to effectively address the pathology. The direct view minimizes the risk of leaving residual compression, ensuring a thorough decompression.[1,4]

iii. **Surgical adaptability:** Surgeons can respond to unexpected findings intraoperatively, such as additional disc fragments or abnormal anatomy, without significant modification to the procedure.[1,4]

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Procedural details

i. **Incision and access:** The surgeon begins with a midline or paramedian incision, typically several centimetres long. The paraspinal muscles are dissected and retracted to expose the bony structures of the spine.[1,4]

ii. **Laminectomy or foraminotomy**: A portion of the lamina or foramen is removed to create space for accessing the affected nerve root.[4,13]

iii. **Removal of pathology:** The herniated disc material is identified and excised carefully to avoid damaging the nerve root or dural sac.[4,13]

iv. **Closure:** Once the decompression is complete, the surgical site is irrigated, and the incision is closed in layers.[4]

Limitations

i. **Invasiveness:** Larger incisions and extensive soft tissue dissection contribute to greater blood loss and postoperative pain. The muscle disruption inherent in these procedures often leads to long-term muscular weakness and scarring.[4]

ii. **Longer recovery periods:** The tissue trauma associated with open procedures necessitates prolonged rehabilitation, delaying return to normal activities or work.[2,4]

iii. **Risk of complications:** Dural tears, epidural fibrosis, and iatrogenic instability remain significant concerns. These complications can lead to additional surgeries, prolonged recovery, and suboptimal patient outcomes (Figure 1).[1,4,10]

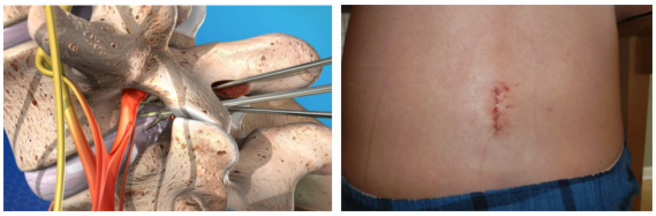

Figure 1 Traditional microdiscectomy technique and post-operative surgical scar.

Long-term considerations

While these procedures are effective, their long-term impact on spinal stability and musculature is a growing concern. Post-laminectomy syndrome, characterized by chronic pain and dysfunction, underscores the need for ongoing innovation in surgical techniques.[4,10,13] Additionally, the increasing focus on patient-reported outcomes has highlighted the limitations of traditional methods in addressing quality-of-life measures beyond pain relief.[14]

By recognizing these challenges, the field has shifted toward minimally invasive alternatives, which aim to preserve tissue integrity, reduce recovery times, and achieve similar or better clinical outcomes. The evolution of these techniques represents a natural progression in the pursuit of optimal patient care.[2,9,15]

Minimally invasive approaches: TELD and related techniques

Minimally invasive techniques have been developed to address the shortcomings of traditional open surgeries. TELD, in particular, utilizes percutaneous access and endoscopic visualization to achieve effective decompression with minimal tissue disruption. The procedure involves inserting a working channel through a small incision to the affected spinal segment, enabling precise removal of herniated disc material while preserving surrounding tissues and stabilizing structures.[1,15–18]

Clinical evidence

Numerous studies have highlighted the clinical benefits of TELD. This approach has emerged as a preferred technique due to several distinct advantages:

i. **Reduced postoperative pain:** The small incision and minimal muscle disruption result in significantly lower pain levels compared to open surgeries. Studies demonstrate that patients report improved comfort in the immediate postoperative period and reduced reliance on opioid analgesics.[1,19]

ii. **Faster recovery:** Patients undergoing TELD typically experience shorter hospital stays and quicker return to daily activities. Enhanced recovery protocols aligned with TELD contribute to the early mobilization and reduced rehabilitation requirements.[1,2,9]

iii. **Improved patient satisfaction:** Enhanced cosmetic outcomes, reduced morbidity, and better functional recovery contribute to higher satisfaction rates. Surveys and patient-reported outcome measures highlight the superior quality of life associated with TELD compared to traditional methods.[1,19]

A meta-analysis by Gadjradj et al. (2021) demonstrated that TELD achieved similar or superior functional outcomes compared to traditional microdiscectomy, with significantly lower complication rates.[1] These findings underscore TELD's growing role as a viable alternative to conventional techniques, particularly in appropriately selected patient populations.

Innovations: integrating biological therapies with TELD

Recent advancements in TELD include the integration of biological therapies such as platelet-rich plasma (PRP). These innovations aim to enhance tissue healing and reduce the risk of recurrence. PRP, rich in growth factors and cytokines, has shown promise in promoting annular repair and mitigating the inflammatory response associated with disc pathology.[5–8] Key mechanisms include:

i. Stimulating cellular proliferation and matrix remodeling: PRP enhances the reparative processes in the annulus fibrosus, aiding recovery and reducing recurrence risk.[8]

ii. Modulating inflammatory responses: Anti-inflammatory properties of PRP contribute to reduced postoperative pain and improved healing.[5,8]

iii. Providing a mechanical barrier: PRP forms a scaffold within the annular defect, preventing further extrusion of disc material.[5,8]

A prospective cohort study by Jiang et al. (2022) demonstrated that TELD combined with PRP injection significantly reduced recurrence rates and facilitated disc remodeling compared to TELD alone.[5,8] These findings support the growing interest in combining MIS techniques with biologically active substances to optimize outcomes.

Expanded technical approaches

TELD continues to evolve with refinements in surgical tools and techniques. Innovations such as real-time imaging integration, advanced irrigation systems, and improved endoscopic visualization have enhanced procedural precision and safety.[2,9,10] Additionally, the development of biportal and uniportal endoscopic systems has expanded the applicability of TELD to address complex spinal pathologies, including:

i. **Calcified disc herniations:** Advanced drilling systems enable the safe removal of calcified fragments.[10,17]

ii. **Recurrent stenosis:** Repeat decompression procedures are performed efficiently with minimal additional tissue disruption.[17]

iii. **Dual-level decompressions:** Biportal systems allow for simultaneous access to multiple segments, reducing operative time and patient morbidity.[2,9,10]

Long-term outcomes and patient selection

While TELD offers numerous advantages, its success depends on careful patient selection. Factors such as the type of disc herniation, degree of stenosis, and spinal alignment influence the appropriateness of TELD.[16] Emerging evidence suggests that combining clinical, radiological, and biomechanical assessments enhances the selection process, ensuring optimal outcomes for diverse patient populations.[9,14,16]

By addressing these factors and incorporating ongoing technological and biological advancements, TELD continues to establish itself as a cornerstone of minimally invasive spinal surgery.[1,9]

Technical aspects of TELD

Procedural details

i. **Patient positioning:** The patient is positioned prone on a radiolucent table, ensuring proper alignment of the spine. The target spinal segment is localized and marked under fluoroscopic guidance to ensure precision.[3,10,15]

ii. **Percutaneous access:** An 18-gauge spinal needle is advanced to the affected segment, guided by fluoroscopy. Once positioned, a guidewire is inserted, maintaining the trajectory toward the intervertebral disc.[3,10,15]

iii. **Dilation and foraminoplasty**: Sequential dilators are introduced over the guidewire to create a working channel. A trephine or bone drill may be employed to enlarge the intervertebral foramen, providing adequate access for the endoscope.[3,10,15]

iv. **Endoscopic decompression:** Under continuous saline irrigation, the working channel accommodates the endoscope, which provides a magnified view of the surgical field. Herniated disc material is visualized and carefully excised using specialized instruments such as forceps or laser systems.[3,10,15]

v. **Annuloplasty and PRP Injection:** In procedures incorporating PRP, the plasma is injected into the annular defect to promote healing and reduce the risk of recurrence. Annuloplasty may also involve sealing the annular tear to enhance stability.[5,8]

vi. **Closure:** The working channel is removed, and the small incision is closed with minimal sutures or adhesive strips, further minimizing scarring and recovery time.[10,15]

Limitations

i. **Steep learning curve:** Surgeons require extensive training and experience to master the intricacies of TELD. Proficiency in fluoroscopic navigation and endoscopic manipulation is critical for success.[10,19]

ii. **Instrumentation costs:** The specialized tools and equipment needed for TELD, including endoscopic systems and advanced imaging technologies, represent a significant financial investment.[11]

iii. **Patient selection:** TELD is most effective for soft disc herniations and localized foraminal stenosis. It is less suitable for cases involving calcified discs, severe instability, or multilevel pathologies (Figure 2).[10,16]

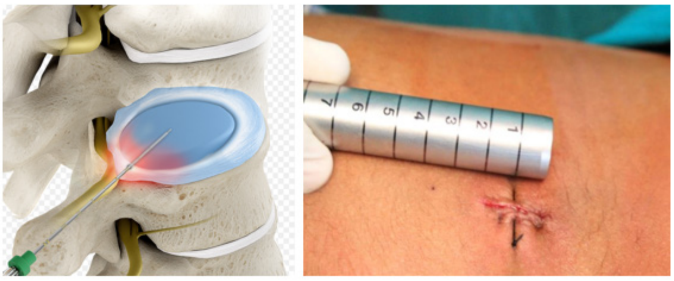

Figure 2 Endoscopic Lumbar Discectomy and post-operative surgical scar.

Comparative analysis

Aspect	Traditional techniques	Minimally invasive techniques
Incision Size	Larger incisions	Small percutaneous incisions
Tissue Trauma	Significant muscle dissection	Minimal tissue disruption
Recovery Time	Longer	Shorter
Recurrence Rate	Moderate	Reduced with PRP integration
Visualization	Direct open view	Endoscopic with magnification
Complications	Higher rates of fibrosis and instability	Reduced dural tears and fibrosis

By integrating advanced techniques, biological innovations, and patient-centered care, TELD exemplifies the evolution of minimally invasive spinal surgery.[1,5,9] As technology continues to advance, TELD and related approaches promise to further transform the landscape of spinal care.[16,19]

Expanding horizons: additional techniques and approaches

Advances in endoscopic equipment

Modern endoscopic systems are becoming increasingly sophisticated, incorporating features such as ultra-high-definition imaging, advanced optics, and ergonomic designs to enhance surgical precision.[9,10] These systems include integrated irrigation channels to maintain a clear surgical field and real-time feedback mechanisms to monitor intraoperative parameters. The development of biportal endoscopy, which involves two working channels for simultaneous visualization and instrumentation, has further expanded the scope of minimally invasive decompression.[2,13,16] This approach enables surgeons to address complex pathologies, such as multilevel stenosis or extensive disc herniations, with greater efficiency and precision.[9]

Additionally, innovations in flexible endoscopic instruments allow for better maneuverability in challenging anatomical regions.

These advancements have significantly reduced the learning curve associated with endoscopic procedures and increased their adoption among spine surgeons.[9,19]

Combination therapies

The integration of mechanical and biological methods has emerged as a promising avenue in spinal surgery. Bone morphogenetic proteins (BMPs), when combined with endoscopic fusion techniques, stimulate osteogenesis and enhance spinal stability in cases requiring structural reinforcement.[5,6,8] For example:

i. **BMP-2 and cage systems**: BMP-2 is commonly used with interbody cages in endoscopic fusion procedures to promote bony fusion and reduce pseudarthrosis rates.[6]

ii. **Autologous bone grafting**: The use of autologous bone grafts in conjunction with endoscopic decompression and fusion provides an additional biological scaffold for bone regeneration.[6,8]

Recent studies suggest that the combined application of BMPs and minimally invasive techniques results in improved fusion rates, reduced operative times, and fewer complications compared to traditional open fusion surgeries.[1,4]

Image-guided navigation

Intraoperative navigation systems and robotic-assisted technologies have revolutionized the accuracy and safety of minimally invasive spinal surgeries. These systems provide:

i. **Real-time imaging**: Advanced fluoroscopy, CT-based navigation, and 3D imaging enable precise localization of spinal anatomy, minimizing the risk of nerve or vascular injury.[11,12]

ii. **Enhanced precision**: Robotic platforms such as Mazor X and ROSA Spine facilitate highly accurate trajectory planning and screw placement, even in anatomically complex cases.[11,12]

iii. **Workflow efficiency**: The integration of navigation systems into operating room workflows reduces the need for repeated imaging and manual adjustments, decreasing overall operative times.[11,12]

Robotic assistance in particular is gaining popularity for its ability to reduce surgeon fatigue and enhance outcomes in long and complex procedures. Augmented reality (AR) overlays, which project anatomical structures onto the surgical field, further enhance visualization and decision-making during surgery (Figure 3).[11,12]

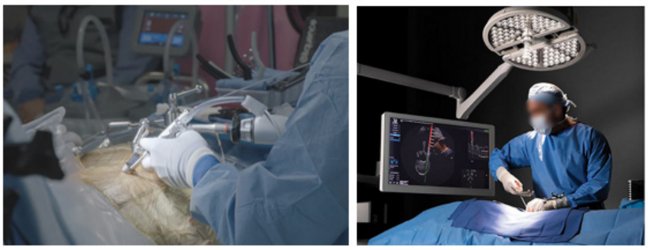

Figure 3 Spinal endoscopic equipment and navigation system.

Future directions

The combination of advanced endoscopic equipment, biological augmentation, and image-guided technologies is paving the way for more effective and less invasive spinal procedures.[1,3] Emerging innovations, such as artificial intelligence (AI)-driven surgical planning and 3D-printed patient-specific implants, promise to further enhance the precision and personalization of spinal care.[12,20] As these technologies continue to evolve, the integration of multidisciplinary approaches will remain central to achieving optimal patient outcomes.

Extending clinical indications for MIS techniques

Advancements in minimally invasive techniques are significantly broadening the range of conditions that can be effectively treated. The development of innovative tools, improved visualization technologies, and enhanced surgical methodologies have allowed surgeons to address complex and previously challenging pathologies with greater precision and efficacy.[1,16]

Spinal stenosis

MIS decompression techniques, such as TELD, are increasingly employed to manage complex central and lateral recess stenosis. Innovations in foraminoplasty and endoscopic drilling enable the precise removal of bony and soft tissue structures compressing the spinal canal or nerve roots.[2,9] Additionally, biportal endoscopy facilitates dual-portal access, allowing for the simultaneous manipulation of instruments and visualization of the surgical field, which is particularly advantageous in multilevel stenosis cases.[2,10]

Spondylolisthesis

The treatment of spondylolisthesis has traditionally relied on open fusion surgeries, often accompanied by significant tissue disruption. However, the advent of percutaneous pedicle screw systems and expandable interbody cages has transformed the approach to spinal stabilization.[3,13] MIS techniques now allow for the effective reduction of vertebral slippage and restoration of sagittal alignment. This minimally invasive approach minimizes muscle trauma, reduces postoperative pain, and accelerates recovery while achieving comparable biomechanical stability.[10,13,16]

Recurrent herniations

Recurrent lumbar disc herniations present a unique challenge due to the risk of additional scar tissue formation and neural damage. TELD, when combined with biological therapies like platelet-rich plasma (PRP) or fibrin sealants, has shown significant promise in reducing recurrence risks.[5,8] These biological adjuncts enhance annular repair and create a barrier to prevent further herniation, improving long-term outcomes.[5] Repeat MIS procedures for recurrent herniations are associated with lower complication rates compared to traditional revision surgeries.[16]

Complex and multilevel pathologies

Advances in endoscopic equipment and navigation technologies have extended MIS applications to complex and multilevel spinal pathologies. Biportal techniques and robotic-assisted systems enable precise decompression and stabilization across multiple vertebral levels, reducing the need for multiple surgeries.[2,9,11] This approach is particularly beneficial for patients with degenerative scoliosis or tandem spinal stenosis.[11,12]

Pathologies beyond the lumbar spine

While MIS techniques are most commonly associated with lumbar pathologies, their indications are expanding to include cervical and thoracic conditions. Endoscopic cervical foraminotomy and discectomy offer effective solutions for foraminal stenosis and disc herniations, while thoracic endoscopy is gaining traction for conditions such as thoracic disc herniation and vertebral fractures.[3,10]

Future directions

The integration of advanced imaging modalities, such as intraoperative CT and augmented reality (AR) overlays, continues to expand the scope of MIS techniques. These technologies improve surgical precision and enable the treatment of conditions that were previously unsuitable for minimally invasive approaches.[11,12] Additionally, the combination of AI-based predictive analytics and patient-specific implants promises to further personalize and optimize MIS interventions.[12,20]

As the clinical indications for MIS techniques continue to grow, the field is moving toward a future where minimally invasive spinal surgery becomes the standard of care across a wide spectrum of pathologies. This progress underscores the importance of ongoing innovation and multidisciplinary collaboration in advancing spinal microsurgery.[1,12]

The role of patient-centered care

Enhanced recovery programs

Minimally invasive techniques align seamlessly with Enhanced Recovery After Surgery (ERAS) protocols, which are designed to optimize surgical outcomes and improve overall patient experiences. These protocols encompass multiple perioperative strategies:

i. **Reducing hospital stays**: By minimizing tissue disruption and postoperative pain, MIS significantly shortens hospital stays. Many patients undergoing minimally invasive procedures can be discharged on the same day, promoting quicker recovery in the comfort of their own homes.[1,4]

ii. **Encouraging early mobilization**: The reduced trauma of MIS facilitates early ambulation. Patients are often encouraged to mobilize within hours of surgery, which reduces the risk of complications such as deep vein thrombosis (DVT) and promotes faster functional recovery.[1,4]

iii. **Decreasing opioid dependence**: MIS procedures typically require less postoperative pain management, reducing reliance on opioid analgesics. This aligns with global efforts to combat the opioid epidemic and encourages the use of multimodal pain management strategies.

Patient education and involvement

Patient education is a cornerstone of patient-centered care in MIS. Providing comprehensive, individualized information about the benefits, risks, and expected outcomes of minimally invasive techniques versus traditional approaches empowers patients to make informed decisions.[4,14] This process includes:

i. **Preoperative counseling**: Detailed discussions about the procedure, recovery timeline, and lifestyle modifications help set realistic expectations and reduce anxiety.[4]

ii. **Educational materials**: Written brochures, videos, and interactive digital content tailored to the patient's condition enhance understanding and engagement.[14]

iii. **Shared decision-making**: Involving patients in treatment planning fosters trust and ensures that their preferences and values are respected.

Effective patient education has been shown to improve adherence to postoperative instructions, enhance satisfaction, and contribute to better clinical outcomes. Moreover, it strengthens the therapeutic alliance between patients and healthcare providers, which is vital for long-term success.

By integrating these principles into perioperative care, minimally invasive spinal surgery continues to set new benchmarks for patient-centered care and clinical excellence.

Challenges and future directions

Challenges

The transition from traditional open surgeries to minimally invasive techniques (MIS) presents several challenges that must be addressed to fully realize the potential of these advancements:

Training and standardization

i. **Surgeon expertise**: The steep learning curve associated with MIS procedures, such as TELD, requires extensive training and hands-on experience. Surgeons must develop proficiency in navigating fluoroscopic imaging, manipulating endoscopic instruments, and performing precise decompressions within a confined space.[16,19]

ii. **Standardized protocols**: Variability in surgical techniques and equipment can lead to inconsistent outcomes. The development of standardized guidelines and training programs is essential to ensure uniformity and high-quality care across institutions.

Cost barriers

i. **High initial investment**: The advanced tools and technologies required for MIS, including endoscopic systems, navigation platforms, and robotics, represent a significant financial burden for healthcare facilities, especially in resource-limited settings.[11]

ii. **Long-term cost-effectiveness**: While the upfront costs are high, MIS techniques have been shown to reduce overall healthcare expenditures through shorter hospital stays, faster recoveries, and lower complication rates. Promoting awareness of these benefits among stakeholders is crucial for widespread adoption.[4,11]

Patient Selection

Not all spinal pathologies are suitable for MIS. Severe instability, extensive calcifications, or multilevel pathologies may necessitate traditional open procedures. Comprehensive preoperative assessments, including imaging and biomechanical analysis, are essential to identify ideal candidates and avoid suboptimal outcomes.[4,16]

Future innovations

The future of spinal surgery is poised for remarkable advancements, driven by technological innovation and interdisciplinary collaboration. Key areas of focus include:

Robotics and augmented reality (AR)

i. **Enhanced precision**: Robotic platforms, such as Mazor X and ROSA Spine, are revolutionizing spinal surgery by enabling highly accurate trajectory planning and screw placement. These systems reduce human error and improve outcomes, particularly in complex cases.[11,12]

ii. **AR integration**: Augmented reality overlays provide real-time anatomical guidance during surgery, enhancing the surgeon's ability to navigate challenging anatomy. This technology improves intraoperative visualization and decision-making.[12]

Advanced biological therapies

i. **Stem cell injections**: Stem cells offer the potential to regenerate damaged disc tissues and restore biomechanical function. Ongoing research aims to refine delivery methods and identify the most effective cell types for spinal applications.[5,8]

ii. **Extracellular matrix products**: These biologically active scaffolds support tissue repair and regeneration, offering new possibilities for annular healing and disc preservation.[6]

iii. **Gene editing**: Techniques such as CRISPR-Cas9 are being explored to address genetic factors contributing to degenerative disc disease, paving the way for personalized regenerative therapies.

Artificial intelligence (AI)

i. **Predictive analytics**: AI algorithms can analyze patient data to predict surgical outcomes, optimize patient selection, and customize treatment plans.[12]

ii. **Machine learning in surgery**: By analyzing large datasets, machine learning models can identify patterns and provide real-time insights, improving surgical planning and intraoperative decision-making.[11,12]

Telemedicine and remote surgery

i. **Expanded access**: Robotic platforms and telemedicine solutions enable expert surgeons to perform or guide procedures remotely. This innovation addresses disparities in access to advanced spinal care, particularly in underserved regions.[11,12]

ii. **Virtual training**: Simulated environments and virtual reality platforms are enhancing surgical training, providing trainees with hands-on experience in MIS techniques without the need for cadaveric specimens.[9]

3D printing and custom implants

i. **Patient-Specific Solutions**: 3D printing enables the creation of customized implants tailored to a patient's unique anatomy. These innovations improve implant integration and reduce complications associated with standard devices.[20]

ii. **Preoperative Planning**: 3D-printed models of patient anatomy allow surgeons to plan and rehearse complex procedures, increasing confidence and accuracy.[20]

Conclusion

Minimally invasive spinal surgery represents a pivotal advancement in the field of spinal care, bridging the gap between clinical efficacy and patient-centered outcomes. Addressing the current challenges, such as training gaps, cost barriers, and the need for precise patient selection, remains essential for its widespread implementation. Collaborative efforts between clinicians, researchers, and industry leaders are paramount to overcoming these obstacles and achieving the full potential of MIS techniques.

The future of spinal surgery is bright, with groundbreaking innovations poised to redefine the standard of care. Robotics and augmented reality are transforming the precision and scope of surgical interventions, while advancements in biological therapies and regenerative medicine offer unprecedented opportunities to restore spinal health. Artificial intelligence and machine learning are enhancing decision-making processes and optimizing surgical outcomes, paving the way for personalized and predictive healthcare. Moreover, the integration of telemedicine and remote surgical technologies is breaking geographical barriers, democratizing access to cutting-edge spinal care for patients in underserved regions. The development of patient-specific implants through 3D printing exemplifies the move toward highly tailored and efficient surgical solutions, further improving patient satisfaction and clinical success rates.

Ultimately, minimally invasive spinal surgery exemplifies the convergence of technology, biology, and clinical expertise, setting new benchmarks for safety, effectiveness, and patient experience. By embracing these advancements and fostering interdisciplinary collaboration, the field of spinal microsurgery is well-positioned to deliver transformative benefits to patients, shaping the future of musculoskeletal health and redefining what is possible in modern Medicine.

Further information about this article

Informed consent for patients' images

The images used in this article were obtained following strict adherence to ethical standards for clinical research. Informed consent was explicitly obtained from all patients whose images are included. This process involved explaining the purpose of using the images for educational and publication purposes, ensuring the patients understood their rights, including the option to withdraw consent at any time. Consent forms were signed by the patients and witnessed by a clinical staff member to validate the process. These consent documents are securely archived in the institutional records of our Clinical Department of Neurosciences, where they remain confidential but accessible if required for audit or verification purposes.

Institutional review board (IRB) or ethics committee approval (ECA)

This study was conducted in compliance with ethical research guidelines and was approved by the NeuroKonsilia® Review Board. The approval process involved submitting a detailed research protocol outlining the study's objectives, methods, and ethical considerations. The protocol was reviewed to ensure the study conformed to ethical standards, including patient safety, privacy, and the minimization of risks.

The IRB approval reference number is 20241020-R43701, and it is archived in our Clinical Department of Neurosciences (research compliance office) for future reference. This approval covers the collection, analysis, and publication of patient data and images within the ethical and legal frameworks governing such studies.

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None.

Conflicts of interest

The authors declare that there are no conflicts of interest.

References

1. Gadjradj PS, Harhangi BS, Amelink J, et al. Percutaneous transforaminal endoscopic discectomy versus open microdiscectomy for lumbar disc herniation: a systematic review and meta-analysis. *Spine (Phila Pa 1976)*. 2021;46(8):538–549.

2. Heo DH, Park CK. Comparative study of unilateral biportal endoscopic surgery and conventional microscopic lumbar decompressive laminectomy. *Global Spine Journal.* 2019;9(2):229–235.
3. Wu W, Liang Y, Zheng Y. Minimally invasive surgery for lumbar spinal stenosis: Current concepts and surgical techniques. *Orthopedic Surgery*. 2020;12(2):564–574.
4. Rasouli MR, Rahimi-Movaghar V, Shokraneh F, et al. Minimally invasive discectomy versus microdiscectomy/open discectomy for symptomatic lumbar disc herniation. *Cochrane Database of Systematic Reviews*. 2014;9:CD010328.
5. Jiang Y, Zuo R, Yuan S. et al. Transforaminal endoscopic lumbar discectomy with versus without platelet-rich plasma injection for lumbar disc herniation: A prospective cohort study. *Pain Res Manag*. 2022:6181478.
6. Zhu W, Kong C, Pan F, et al. Engineered collagen-binding bone morphogenetic protein-2 incorporated with platelet-rich plasma accelerates lumbar fusion in aged rats with osteopenia. *Exp Biol Med*. 2021;246(14):1577–1585.
7. Xuan Z, Yu W, Dou Y, et al. Efficacy of platelet-rich plasma for low back pain: A systematic review and meta-analysis. *J Neurol Surg A Centr Eur Neurosurg.* 2020;81(6):529–534.
8. Pirvu TN, Schroeder JE, Peroglio M, et al. Platelet-rich plasma induces annulus fibrosus cell proliferation and matrix production. *Eur Spine J*. 2014;23(4):745–753.
9. Kim HS, Wu PH, Jang IT. Advances in percutaneous endoscopic lumbar discectomy and techniques. *Asian Spine Journal.* 2022;16(2):234–246.
10. Choi G, Pophale CS, Patel B, et al. Endoscopic spine surgery. Journal of Spine Surgery. 2017;2(2):66–77.
11. Scholler K, Alimi M, Cong GT, et al. Robotic-assisted spine surgery: A systematic review of indication, efficacy, and safety. *European Spine Journal*. 2020;29(6):1319–1335.
12. Guiot BH, Khoo LT. Robotics and minimally invasive spine surgery: State of the art. *Neurosurgery.* 2016;79(3):214–225.
13. Kanno H, Aizawa T, Hahimoto A, et al. Minimally invasive discectomy for lumbar disc herniation. *Neurosurgery Clinics of North America*. 2015;26(2):331–336.
14. Aebi M. Spinal disorders in older adults. *The Lancet*. 2019;394(10198):1683–1691.
15. Ahn Y. Current techniques of endoscopic decompression in spine surgery. Annals of Translational Medicine. 2019;7(Suppl 5):S169.
16. Pan M, Li Q, Li S, et al. Percutaneous endoscopic lumbar discectomy: Indications and complications. *Pain Physician*. 2020;23(1):49–56.
17. Mahatthanatrakul A, Kotheeranurak V, Lin GX, et al. Comparative analysis of intervertebral disc signal and annulus changes after transforaminal endoscopic lumbar discectomy and annuloplasty. *Neuroradiology.* 2019;61(4):411–419.
18. Miller LE, Allen RT, Duhon B. Expert review with meta-analysis of Barricaid annular closure in patients at high risk for lumbar disc reherniation. *Expert Rev Med Devices*. 2020;17(5):461–469.
19. Son S, Ahn Y, Lee SG, et al. Learning curve of percutaneous endoscopic transforaminal lumbar discectomy by a single surgeon. *Medicine*. 2021;100(4):e24346.
20. Li X, Dou Q, Meng F, et al. The application of 3D printing technology in spine surgery. *Orthopaedic Surgery.* 2017;9(3):257–263.