

Current Application Status and Development Trends of Minimally Invasive Techniques in the Treatment of Spinal Fractures

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Abstract: Spinal fractures are a common orthopedic injury, with thoracolumbar fractures being the most prevalent. These fractures are often accompanied by nerve damage, severely impacting patients' lives, health, and quality of life. In recent years, minimally invasive techniques have gradually replaced traditional open surgery as the mainstream approach for treating spinal fractures, owing to their advantages of minimal trauma, rapid recovery, and fewer complications. This article reviews the current clinical application status of mainstream minimally invasive procedures, including percutaneous vertebroplasty, percutaneous pedicle screw fixation, and percutaneous endoscopic lumbar discectomy. It analyzes the indications, advantages, and limitations of each technique. Furthermore, by integrating digital and intelligent technologies, it explores the future development trends of minimally invasive techniques in the treatment of spinal fractures, providing references for optimizing clinical treatment plans and technological innovation.

Keywords: Spinal fractures; Minimally invasive techniques; Percutaneous vertebroplasty; Pedicle screw fixation; Intelligent surgery

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1. Introduction

The spine, as the central structure for weight-bearing and neural transmission in the human body, is prone to fractures caused by direct or indirect trauma. While fractures in young and middle-aged adults are predominantly induced by trauma, the elderly are more susceptible to fragility fractures due to osteoporosis ^[1]. Traditional open surgery requires extensive muscle dissection through a long incision to achieve fracture reduction and fixation. However, this approach is associated with significant trauma, substantial intraoperative bleeding, slow postoperative recovery, and a high risk of complications such as infection, nerve injury, and those related to prolonged bed rest, posing numerous obstacles to patient rehabilitation ^[2]. With the rapid advancements in medical imaging, endoscopic techniques, biomaterials science, and precision instrument manufacturing, minimally invasive

technology has transitioned from exploration to maturity in the treatment of spinal fractures. The core principle of minimally invasive approaches is to achieve optimal therapeutic outcomes with minimal trauma. By employing precise localization, small incisions, and visualization techniques, these methods maximize the preservation of the integrity of the soft tissues surrounding the spine and minimize surgical interference with the body. Currently, minimally invasive techniques have been widely applied in the treatment of various types of spinal fractures, significantly improving patient prognosis. Based on recent clinical practice and technological advancements, this review summarizes the current application status and future development trends of minimally invasive techniques in the treatment of spinal fractures, providing a reference for clinical diagnosis and treatment.

2. Application status

2.1. Percutaneous vertebroplasty and percutaneous kyphoplasty

Percutaneous vertebroplasty (PVP) and percutaneous kyphoplasty (PKP) are core minimally invasive surgical procedures for treating osteoporotic vertebral compression fractures^[3,4]. Both involve percutaneous injection of bone cement into the affected vertebra to form an internal scaffold, thereby stabilizing the fracture site and relieving pain. These techniques have been widely applied in clinical practice. PVP offers advantages such as simple operation, minimal trauma, rapid pain relief, early ambulation, and low cost^[5]. PKP incorporates an additional balloon dilation step compared to PVP. It can restore the height of the collapsed vertebra through balloon expansion, providing certain fracture reduction and deformity correction effects. This makes it more suitable for patients with more severe vertebral compression^[6]. Clinical practice has demonstrated that both procedures can significantly alleviate patient pain, improve spinal function, and reduce complications associated with prolonged bed rest. Compared to traditional conservative treatment and open surgery, they exhibit more prominent advantages. Currently, PVP and PKP have been gradually promoted in hospitals at all levels, but they still have certain limitations. Bone cement leakage is the primary complication, which can lead to serious issues such as nerve compression and pulmonary embolism^[7]. The risk of adjacent vertebral re-fracture after surgery also cannot be ignored, which is closely related to stress transfer after bone cement reinforcement and the ineffective control of the underlying osteoporosis disease in patients. Therefore, strict control of indications is necessary in clinical application. Preoperative imaging examinations should be used to assess the integrity of the posterior vertebral wall, standardized intraoperative operations should be performed to control bone cement injection, and postoperative anti-osteoporosis treatment should be combined to reduce the risk of recurrence.

2.2. Percutaneous pedicle screw fixation

Percutaneous pedicle screw fixation is mainly applicable to traumatic thoracolumbar fractures, especially showing significant advantages for stable and some unstable fractures that do not require direct decompression^[8]. Under image guidance, this technique involves inserting pedicle screws through small skin incisions via the intermuscular space, without the need for extensive dissection of the paravertebral muscles. It can maximize the preservation of the stability of the posterior spinal muscle-ligament complex, aligning with the concept of minimally invasive treatment. Compared to traditional open internal fixation surgery, percutaneous pedicle screw fixation has obvious advantages in terms of trauma control and postoperative recovery. Intraoperative blood loss is significantly reduced, postoperative pain levels are markedly decreased, and patient hospital stays are noticeably shortened, enabling patients to return to normal life more quickly^[9]. Meanwhile, this technique can achieve the same fracture

reduction accuracy and fixation stability as traditional open surgery, and the incidence of long-term complications such as postoperative muscle atrophy and chronic low back pain is significantly lower. In recent years, the application scope of this technique has gradually expanded. By combining it with percutaneous laminectomy for decompression, it can be used for some burst fractures with spinal canal occupation. However, this technique has high requirements for surgical instruments and operational precision, with a relatively long learning curve. Its application is limited in patients with severe osteoporosis or abnormal vertebral anatomical structures, and there are potential risks such as screw loosening and pullout. Clinical application should strictly follow operational specifications.

2.3. Percutaneous transforaminal endoscopic technique

The percutaneous transforaminal endoscopic technique establishes a minimally invasive channel through the intervertebral foramen and directly addresses issues such as nerve compression by fracture fragments and intervertebral disc injury under endoscopic visualization. It features minimal trauma, a clear field of view, and rapid recovery ^[10]. Initially, this technique was mostly used for the treatment of lumbar disc herniation and spinal stenosis. In recent years, it has gradually extended to the field of spinal fractures, especially being suitable for thoracolumbar fracture patients with intervertebral disc injury and nerve root compression. Percutaneous transforaminal endoscopic surgery involves a tiny incision and can precisely remove fracture fragments and intervertebral disc tissue that compress the nerves, avoiding extensive spinal canal exploration and reducing the risk of nerve injury. At the same time, it can maximize the preservation of the integrity of the spinal structure and reduce the occurrence of postoperative spinal instability ^[11]. After surgery, patients experience rapid pain relief and a short recovery period, enabling them to quickly return to normal life. Compared to traditional open decompression surgery, its minimally invasive advantages are more prominent. Currently, the application of percutaneous transforaminal endoscopic technique in cervical and thoracic spine fractures is still in the exploratory stage. Due to factors such as the complex anatomical structure of the upper spine and the narrow operating space, its indication scope is relatively narrow. For patients with large fracture fragments and severe spinal canal occupation, the percutaneous transforaminal endoscopic technique alone is difficult to achieve ideal therapeutic effects, and it needs to be combined with other minimally invasive techniques or open surgery to ensure treatment efficacy.

3. Development trends

3.1. Deep integration of intelligent and digital technologies

The deep integration of intelligent and digital technologies with spinal surgery is reshaping the entire process of minimally invasive treatment for spinal fractures. Artificial intelligence (AI) technology has extended from simple image recognition to clinical decision support, enabling functions such as spinal parameter measurement, fracture classification judgment, and postoperative complication prediction. This significantly enhances the efficiency and accuracy of preoperative planning, providing a scientific basis for formulating surgical plans ^[12]. The core breakthrough of robotic navigation technology lies in improving surgical precision and safety, gradually achieving a “radiation-free” surgical process ^[13]. Relying on advanced imaging technologies, robotic navigation enables high-precision operations without additional radiation, particularly suitable for treating special populations while reducing the risk of surgeon fatigue and radiation exposure. The development of remote robotic technology further

breaks down geographical barriers in healthcare resources, enabling patients in remote areas to access high-quality and precise minimally invasive treatment services. The maturity of synthetic imaging technology allows for the generation of bone imaging results from conventional images through deep learning, meeting navigation accuracy requirements while avoiding the complexity and radiation associated with multimodal imaging examinations, and promoting the development of minimally invasive surgery towards “radiation-free, single-modality imaging.” In the future, the collaborative application of AI and robotic technologies will enable fully automated planning and precise operations throughout the surgical process, further enhancing the safety and effectiveness of minimally invasive treatment ^[14].

3.2. Research and application of new biomaterials

The innovation of biomaterials is a crucial support for advancing minimally invasive treatment for spinal fractures. Currently, 3D-printed porous titanium alloy implants, with their bionic structural advantages, can promote bone tissue ingrowth and improve the biocompatibility between the implant and the vertebrae, demonstrating excellent performance in spinal fusion surgeries and gradually becoming the mainstream of next-generation fusion implant materials ^[15]. Addressing the limitations of traditional bone cement, research on degradable bone cement has made progress, achieving early fixation effects while gradually degrading to avoid adjacent vertebral damage caused by long-term stress shielding, providing good support for bone tissue repair. Research on non-fusion materials such as viscoelastic artificial intervertebral discs and vertebral tethering materials continues to deepen, offering new directions for preserving spinal motion function. Among them, vertebral tethering technology can achieve precise correction and dynamic fixation in the treatment of spinal deformities combined with fractures, reducing the risk of overcorrection and providing more options for treating complex cases ^[16]. In the future, intelligent materials that combine fixation stability and bioactivity will achieve the integrated goal of “fixation-repair-functional reconstruction,” further optimizing the outcomes of minimally invasive treatment.

3.3. Expansion of indications and optimization of surgical techniques for minimally invasive treatment

As technologies mature and instruments improve, the indications for minimally invasive techniques will gradually expand to include complex spinal fractures. For burst fractures accompanied by spinal cord injury and severe spinal canal occupation, the combined surgical approach of “minimally invasive fixation + endoscopic decompression” will gradually become widespread, achieving thorough decompression and rigid fixation while minimizing trauma, balancing efficacy and minimally invasive advantages ^[17]. Percutaneous endoscopic lumbar discectomy technology will break through anatomical limitations in the cervical and thoracic spine through the development of specialized instruments and optimization of navigation systems, expanding its application in upper spinal fractures. The optimization and refinement of non-fusion techniques represent an important future development direction. For complex cases such as adult spinal deformities combined with fractures, preventive fixation techniques will be adopted by improving scoring systems and surgical strategies to reduce the incidence of mechanical complications ^[18]. For elderly patients with osteoporotic fractures, a comprehensive treatment model of “minimally invasive reinforcement + anti-osteoporosis + rehabilitation training” will be established, effectively reducing the risk of re-fracture and improving long-term patient outcomes through standardized postoperative interventions ^[19].

3.4. Popularization of precision and personalized treatment

In the future, minimally invasive treatment for spinal fractures will transition from “standardization” to “personalization,” achieving precise diagnosis and treatment. 3D-printed personalized navigation templates based on patient imaging data can precisely adapt to the anatomical differences of different patients’ vertebrae, optimizing puncture paths and internal fixation positions, and enhancing surgical precision. AI models will integrate multidimensional information such as patient age, bone density, fracture type, and comorbidities to assist in generating optimal treatment plans, predicting surgical risks and rehabilitation outcomes, and providing scientific support for clinical decision-making ^[20]. The multidisciplinary collaboration model will be further refined, with close cooperation among orthopedics, radiology, rehabilitation, anesthesiology, and other departments to develop personalized, full-cycle plans for complex spinal fracture patients covering preoperative evaluation, surgical operations, and postoperative rehabilitation. Meanwhile, patient preferences will be fully incorporated into treatment decisions, seeking the best balance between efficacy and quality of life, reflecting the humanistic care of medical technology, and promoting the development of minimally invasive treatment towards greater precision and alignment with patient needs.

4. Conclusion

Significant progress has been made in the application of minimally invasive techniques for the treatment of spinal fractures. Standardized clinical pathways have been established for mainstream procedures such as percutaneous vertebroplasty and percutaneous pedicle screw fixation. Leveraging advantages such as minimal trauma, rapid recovery, and fewer complications, these techniques have significantly improved the treatment experience and prognosis for patients. With continuous innovations in intelligent technologies, novel biomaterials, and minimally invasive instruments, minimally invasive treatment for spinal fractures is advancing towards precision, intelligence, and personalization. Surgical accuracy, safety, and efficacy will be further enhanced, with an expanding range of indications, providing more high-quality options for treating complex spinal fractures. In the future, through multidisciplinary collaborative innovation and deep integration of technologies, minimally invasive techniques will achieve the goals of “maximizing therapeutic efficacy, minimizing trauma, and optimizing function” in spinal fracture treatment, offering patients superior medical services and driving sustained development in the field of spinal surgery.

Disclosure statement

The authors declare no conflict of interest.

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