Advances in Minimally Invasive Treatment of Osteoporotic Spinal Fractures

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Abstract: Osteoporotic spinal fracture is a common orthopedic condition, currently often treated with surgical intervention. Among these, minimally invasive surgery has become the mainstream treatment option due to its advantages such as rapid recovery and minimal trauma. Based on the pathological characteristics of osteoporotic spinal fractures, this paper reviews common minimally invasive treatment techniques, including percutaneous kyphoplasty and percutaneous vertebroplasty, and analyzes the mechanisms of action and clinical efficacy of various techniques, aiming to provide a reference for clinical treatment.

***Keywords*:** osteoporosis, spinal fractures, minimally invasive treatment

1. Introduction

Osteoporotic vertebral compression fracture (OVCF) is a common complication of osteoporosis, with a markedly higher incidence among individuals over 50 years of age, affecting approximately one-fifth of men and one-third of women, according to the CSOBMR 2022 expert consensus on the diagnosis and management of osteoporotic vertebral compression fractures. Its prevalence increases progressively with age. After the onset of OVCF (Osteoporotic vertebral compression fracture), patients often present with spinal deformity and pain, which can, in severe cases, restrict daily activities and significantly reduce quality of life. The main treatment options include conservative therapy and surgical intervention; however, conservative treatment has gradually been limited due to its long convalescence and higher risk of complications [1]. With the widespread application of minimally invasive techniques in orthopedics, minimally invasive surgery has gradually become the preferred clinical option for treating OVCF, as it can significantly improve therapeutic outcomes and enhance patient prognosis.

2. Pathological Characteristics of Osteoporotic Vertebral Fractures

Epidemiological studies have shown that among individuals over the age of 50, approximately 10.0% of men and 20.0% of women experience vertebral fractures, with incidence steadily increasing with advancing age. In populations over 80 years old, the prevalence reaches nearly 40.0%. Clinical studies indicate that osteoporotic patients with vertebral fractures not only have a higher risk of disability but also a 30.0%–40.0% likelihood of requiring long-term care. From a pathological perspective, the core mechanisms involve a reduction in bone mass and deterioration of the bone microarchitecture [2]. Osteoporosis leads to decreased bone mineral density and thinning of cortical bone and trabeculae structures, resulting in reduced bone strength. As the spine is the primary weight-bearing structure of the body, vertebrae become increasingly vulnerable to fracture — particularly in high-stress regions such as T12–L1. Once the bone microarchitecture is compromised, vertebral compressive strength decreases and spinal instability develops, resulting in vertebral height loss, spinal deformity, and, in severe cases, nerve compression and disability.

3. Minimally Invasive Surgical Techniques for Osteoporotic Vertebral Fractures

In the treatment of Osteoporotic vertebral compression fracture (OVCF), the primary surgical objectives are to relieve pain, restore spinal stability, and reduce the risk of refracture. Both open surgery and minimally invasive surgery can facilitate the restoration of vertebral height. Techniques such as internal fixation and bone cement augmentation further enhance spinal stability and improve health-related quality of life [3]. In recent years, with the aging population and the increasing prevalence of osteoporosis, the limitations of traditional open surgery in pain control, recovery duration, and postoperative complications have become increasingly apparent. In contrast, minimally invasive techniques offer significant advantages in shortening the rehabilitation period, reducing intraoperative blood loss, and lowering the incidence of postoperative complications. However, different technical approaches — such as percutaneous vertebroplasty (PVP), percutaneous kyphoplasty (PKP), and expandable vertebral plasty — still vary in their effectiveness at restoring vertebral height, alleviating pain, and reducing the risk of refracture. Therefore, clinical selection should be individualized based on the patient’s bone quality, degree of vertebral collapse, and radiographic characteristics.

3.1 Percutaneous Vertebroplasty (PVP)

PVP is one of the earliest minimally invasive procedures developed for the treatment of osteoporotic vertebral fractures. It involves percutaneous puncture and injection of bone cement into the fractured vertebral body. The exothermic polymerization reaction of the bone cement ablates pain-transmitting nerve fibers within the vertebra, stabilizes the fractured vertebral body, prevents further loss of vertebral height, and may partially contribute to vertebral height restoration. Clinical studies have shown that PVP can relieve pain in 70.0%–90.0% of OVCF patients, enabling them to ambulate early and thus preventing complications associated with prolonged bed rest. Ding Peng [4] reported that the treatment effectiveness rate after PVP was 96.00%, and that postoperative anterior/posterior vertebral height and Cobb angle significantly differed from those in the control group, further confirming the clinical value of this procedure.

In percutaneous vertebroplasty, the choice between unilateral and bilateral pedicle approaches is an important decision-making point. The unilateral pedicle approach offers advantages such as shorter operative time, fewer punctures, and reduced tissue trauma, thereby reducing intraoperative bleeding and the risk of puncture-related complications. It is particularly suitable for patients with poor tolerance or compromised general condition. However, unilateral access may result in uneven distribution of bone cement within the vertebra, especially in cases where the vertebral transverse diameter is large, leading to insufficient reinforcement on the contralateral side and potentially affecting the surgical outcome.

By contrast, the bilateral approach allows for more uniform dispersion of bone cement on both sides of the vertebra, promoting restoration of biomechanical stability and reducing the risk of postoperative uneven stress distribution. Nevertheless, this approach is technically more complex, requires a longer operative time, and involves two punctures, which increase tissue trauma and complication rates.

Clinical practice suggests that, to ensure optimal surgical outcomes, comprehensive preoperative imaging (such as CT or MRI) should be performed to assess fracture morphology and vertebral anatomy. Intraoperatively, fluoroscopic guidance (C-arm) should be used to adjust puncture angle and control cement injection speed, thereby optimizing cement distribution and improving procedural safety.

However, studies have also shown that although percutaneous vertebroplasty (PVP) has significant advantages in improving vertebral height and alleviating pain, it has certain limitations, the most notable of which is postoperative bone cement leakage. Leakage may occur into the intervertebral disc space, neural foramen, or paravertebral soft tissues, and in severe cases, it can enter the vertebral venous system, travel with the bloodstream to the lungs, and cause pulmonary embolism, leading to pulmonary embolism with potentially fatal sequelae such as hemoptysis or chest pain.

In addition, this procedure may induce other complications, including acute infection and bone marrow microthrombosis [5]. Therefore, to minimize the incidence of postoperative complications, strict control of the bone cement injection volume is required, which should be determined according to vertebral size and fracture severity to prevent excessive filling and reduce leakage risk. High-viscosity bone cement preferred because its lower flowability helps decrease the risk of leakage. CT guidance is recommended to ensure accurate puncture site localization and to allow real-time observation of cement distribution during injection, enabling early detection of potential leakage and timely intervention, thereby reducing complications associated with Operations performed without adequate imaging guidance.

Overall, PVP is more suitable for patients with single-level vertebral fractures, mild to moderate collapse, and no significant kyphotic deformity. Its main advantages lie in its technical simplicity and rapid postoperative pain relief. However, because it cannot effectively restore vertebral height, some cases have shown an increased risk of adjacent vertebral refractures during long-term follow-up. Therefore, for patients with significant vertebral compression or kyphotic deformity, PKP or mechanically expandable techniques should be considered to achieve better structural reconstruction outcomes.

3.2 Percutaneous Kyphoplasty (PKP)

PKP was developed as an advancement of percutaneous vertebroplasty. Before bone cement injection, a balloon is percutaneously inserted into the compressed vertebral body and inflated to restore vertebral height and correct kyphotic deformity. Once the desired reduction is achieved, bone cement is injected into the created cavity. Compared with PVP, PKP provides superior restoration of vertebral height and helps prevent the progression of kyphotic deformity while alleviating pain through the reduction of nociceptive stimulation. Moreover, the cavity formed by balloon expansion reduces injection pressure during cement delivery, thereby lowering the risk of cement leakage.

Clinical studies have reported that PKP results in partial vertebral height restoration in approximately 30.0%–40.0% of patients and produces significantly greater Cobb angle correction than PVP. The presence of a cavity also allows for more uniform cement distribution, reducing the incidence of cement leakage by about 18.0%. Zeng Liangping [6] compared

PVP (control group) and PKP (observation group) in patients with multiple osteoporotic vertebral fractures. The results showed that the observation group had a reduced fracture healing duration, smaller Cobb angle at 3 months postoperatively, greater anterior/posterior vertebral height, and a lower complication rate of 2.50%, confirming the clinical value of PKP and supporting its superiority over PVP.

However, there is still no consensus on the optimal approach for PKP. Some researchers advocate unilateral transpedicular access, citing its smaller surgical trauma, shorter operative time, reduced risk of puncture-related complications, and lower healthcare costs. Others argue that bilateral transpedicular access provides better filling of bone cement within the vertebral body, allows a reduced amount of cement per side, and lowers the risk of cement leakage.

Bone cement dispersion is a key factor affecting the efficacy of percutaneous kyphoplasty (PKP). Although the cavity created by balloon expansion provides space for cement injection and facilitates more uniform distribution, cement dispersion can still be influenced by multiple factors, including the degree of balloon expansion and the viscosity of the cement. Therefore, intraoperative real-time imaging guidance is essential. Surgical parameters should be adjusted according to the vertebral condition to ensure homogeneous dispersion of bone cement and adequate filling of the cavity, thereby achieving optimal vertebral stabilization [7].

In addition, several strategies can be employed to minimize the risk of cement leakage: selecting bone cement with an appropriate viscosity—preferably of medium viscosity, which provides sufficient dispersion during injection while lowering leakage risk; determining the injection volume based on the size of the balloon-expanded cavity to avoid overfilling; and using preoperative MRI to identify fracture lines so that cement injection can avoid these areas, further reducing the likelihood of leakage.

3.3 Expandable Vertebral Plasty

Expandable vertebral plasty was developed on the basis of the above two techniques, with its core principle being the restoration of vertebral height through the use of a mechanical expansion device, followed by bone cement injection to optimize vertebral reduction and improve cement safety. Compared with percutaneous kyphoplasty, this technique offers several significant advantages: ①Reduced cement usage and lower leakage risk. By expanding the vertebra from multiple directions with a focus on height restoration, the vertebral body is evenly pressurized and bone cement is better driven into cancellous bone, thus lowering the likelihood of postoperative leakage [8]. ②Simplified procedure. The availability of expansion devices in various sizes allows for effective restoration of the diseased vertebral height with a straightforward operative process. ③Stronger reduction capability. Mechanical expansion provides continuous and controllable force, producing superior reduction results compared to balloon expansion, especially for severe compression fractures. ④Improved safety. Since no balloon is used, there is no risk of balloon rupture interfering with surgical progress. ⑤Better stability. Some expansion devices provide immediate structural support to the fractured vertebra, preventing recollapse before cement solidification. ⑥Reduced operative duration and healthcare expenditure. The expansion device is easily removed after use and does not remain in the vertebra. Yang Yong [9] reported that patients treated with expandable vertebral plasty had significantly less intraoperative blood loss and shorter operative time compared with those undergoing traditional open posterior decompression and fixation. Postoperatively, pain scores, Cobb angle, with improved Cobb angle correction, reduced complication rates, and lower postoperative pain scores in the expandable plasty group, demonstrating its high clinical value in the treatment of osteoporotic vertebral fractures.

It is worth noting that although expandable vertebral plasty demonstrates outstanding performance in vertebral reduction and biomechanical stability, its clinical application remains limited by factors such as device cost, learning curve, and the long-term mechanical stability of bone cement after surgery. Future research should focus on the development of high-strength, bio-compatible, and absorbable materials, as well as intelligent pressure-controlled injection systems, to achieve dual optimization of safety and therapeutic efficacy.

3.4 Postoperative Follow-up

For patients with osteoporotic vertebral fractures, long-term follow-up is necessary regardless of which minimally invasive procedure is performed. Continuous follow-up allows monitoring of vertebral height changes, maintaining correction, assessing pain relief, and surveilling long-term complications, and surveillance for long-term complications such as adjacent vertebral fractures [10]. Moreover, follow-up provides an opportunity for targeted health education, including advice to avoid excessive loading, modify dietary structure, and perform appropriate back and core muscle strengthening exercises. Such guidance helps patients restore spinal function more effectively, improve long-term prognosis, and enhance overall quality of life.

4. Conclusion

In summary, osteoporotic vertebral fracture has become a major health concern, and restoring vertebral height while improving treatment outcomes has become a research focus in recent years. Minimally invasive surgery is currently regarded as the preferred treatment strategy. Techniques such as percutaneous vertebroplasty, percutaneous kyphoplasty, and expandable vertebral plasty have achieved significant success in the management of OVCF. However, each of these procedures has its own advantages and limitations. Therefore, treatment should be individualized according to patient condition. In addition, intraoperative CT guidance, standardized bone cement handling, and structured long-term follow-up should be emphasized to significantly alleviate symptoms and further improve clinical outcomes.

Future development of minimally invasive techniques for osteoporotic vertebral fractures will likely focus on precision and safety enhancement through digital navigation, robotic assistance, and intelligent cement delivery systems. The emergence of bioresorbable and osteoconductive materials may further improve long-term outcomes. Continued clinical trials and long-term data will be essential to refine treatment standards and promote individualized management.

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