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ORIGINAL RESEARCH

Safety and Accuracy of 3D Printing Combined with Intraoperative CT-Guided Percutaneous Vertebroplasty (PVP) for Thoracolumbar Osteoporotic Fractures

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Objective: This study assesses the safety and precision of percutaneous vertebroplasty (PVP) for thoracolumbar osteoporotic fractures using 3D printing and intraoperative CT guidance.

Methods: This retrospective cohort study included 100 patients with thoracolumbar osteoporotic fractures who underwent PVP from January 2020 to December 2022. Preoperative CT scans were used to create 3D printed models for surgical planning and simulation. Intraoperative CT was employed post-needle insertion and pre-cement injection for accuracy verification. Outcomes were measured using the visual analog scale (VAS) for pain, Oswestry disability index (ODI) for functionality, and assessments of vertebral height and kyphotic angle. Complications recorded included cement leakage, nerve injury, and adjacent vertebral fracture. Subgroup analysis was performed to compare outcomes between thoracolumbar and lumbar fractures.

Results: Average operation time was 35.6 ± 8.4 minutes, and fluoroscopy time was 12.3 ± 3.7 seconds. Intraoperative CT confirmed precise needle placement, with no occurrences of cement leakage or nerve injury. VAS scores improved from 8.2 ± 1.5 preoperatively to 2.1 ± 0.9 postoperatively, and ODI scores from 72.3 ± 9.8% to 18.4 ± 6.7%. Subgroup analysis showed no significant differences in clinical or radiographic outcomes between thoracolumbar and lumbar groups, although a higher cement volume was used in lumbar vertebrae (3.6 vs 2.8 mL, $p<0.001$). There was significant post-surgical restoration and maintenance of vertebral height and kyphotic angle, with no adjacent vertebral fractures reported.

Conclusion: PVP using 3D printing and intraoperative CT for thoracolumbar osteoporotic vertebral fractures is safe, accurate, and effective in pain relief, functional improvement, and vertebral morphology restoration. The 3D models enhance surgical planning, while intraoperative CT provides real-time feedback for needle and cement placement.

Keywords: percutaneous vertebroplasty, 3D printing, intraoperative CT guidance, osteoporotic vertebral fractures

Introduction

Osteoporotic vertebral fractures are common complications of osteoporosis, which can cause severe pain, disability, and deformity. The incidence of osteoporotic vertebral fractures is increasing with the aging of the population, and it is estimated that about 25% of postmenopausal women and 40% of men over 80 years old will suffer from at least one osteoporotic vertebral fracture in their lifetime.[1] The conservative therapy for osteoporotic vertebral fractures include bed

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rest, analgesics, and brace immobilization, which may lead to prolonged hospitalization, muscle atrophy, pulmonary infection, and refracture, with limited efficacy.[2]

Percutaneous vertebroplasty (PVP), a minimally invasive procedure involving the injection of bone cement into the fractured vertebrae, can provide immediate pain relief, stabilize the fracture, and prevent further collapse of the vertebrae under fluoroscopic guidance.[3] PVP has been widely used for the treatment of osteoporotic vertebral fractures, and many studies have demonstrated its safety and efficacy.[4,5] However, PVP also has some drawbacks and challenges, such as the difficulty of accurate needle placement, the risk of cement leakage, and the lack of real-time feedback and confirmation of the cement injection.[6,7]

3D printing is a novel technology that can create customized and complex structures based on digital models, which has been applied in various fields of surgical planning, simulation, education, and implantation.[8,9] 3D printing can also be used to fabricate patient-specific models of the fractured vertebrae, which can help the surgeons to understand the anatomy of the fracture through designing the optimal needle trajectory and cement volume.[10,11] In addition, 3D printing can also be combined with intraoperative CT guidance, which can provide real-time images of the needle placement and cement injection accordingly.[12,13]

In this study, we aimed to evaluate the safety and accuracy of PVP for thoracolumbar osteoporotic vertebral fractures using 3D printing combined with intraoperative CT guidance. To the best of our knowledge, this is the first study to report the results of PVP using 3D printing combined with intraoperative CT guidance for thoracolumbar osteoporotic vertebral fractures.

Materials and Methods

Patients

This study was conducted in accordance with the Declaration of Helsinki. It was approved by the Ethics Committee of Langfang People's Hospital and informed consent was obtained from all the patients. All procedures involving human participants were carried out in compliance with the ethical principles and guidelines outlined in the Declaration of Helsinki, ensuring the protection of participants' rights, safety, and well-being throughout the research process. A total of 100 patients with thoracolumbar osteoporotic vertebral fractures who underwent PVP using 3D printing combined with intraoperative CT guidance from January 2020 to December 2022 were retrospectively analyzed. The inclusion criteria were: (1) single-level thoracolumbar osteoporotic vertebral fracture confirmed by radiography and CT; (2) severe back pain that was refractory to conservative therapy for more than 2 weeks; (3) bone mineral density (BMD) less than −2.5 standard deviations (SD) of the young adult mean value measured by dual-energy X-ray absorptiometry (DXA); and (4) no neurological deficit or spinal instability. The exclusion criteria were: (1) infection, tumor, or trauma-related vertebral fracture; (2) severe osteoporosis with multiple vertebral fractures or severe vertebral collapse; (3) coagulation disorders or allergy to bone cement; and (4) contraindications to CT scan, such as patients with severe claustrophobia. The focus on T11-L1 vertebral fractures was intentional, as these regions represent the most common sites for osteoporotic vertebral fractures and have the highest clinical impact in terms of pain and functional disability. Additionally, these segments have unique anatomical considerations that benefit particularly from precise surgical planning.The demographic and clinical characteristics of the patients are shown in Table 1.

3D Printing

The 3D printing models of the fractured vertebrae were fabricated based on the preoperative CT images. The CT images were acquired using a 64-slice CT scanner (Siemens SOMATOM Definition Edge, Germany) with the following parameters: tube voltage 120 kV, tube current 250 mA, slice thickness 1.0 mm, and reconstruction interval 0.5 mm. The CT images were imported into a 3D reconstruction software (Mimics Innovation Suite version 21.0, Materialise, Belgium) and segmented to obtain the 3D models of the vertebrae using a threshold-based method (Hounsfield unit range: 226–3071). The 3D models were then exported to a 3D printing software (3-matic version 13.0, Materialise, Belgium) and modified to create the 3D printing models. The 3D printing models were hollowed to reduce the material consumption and printing time, (shell thickness 2.0 mm), and a hole was created at the pedicle of the fractured vertebra to

Table 1 Demographic and Clinical Characteristics of the Patients

Variable	Value
Number of patients	100
Age (years)	68.4 ± 7.9
Sex (male/female)	38/62
Fracture level (T11-L2)	52/48
BMD (g/cm2)	0.67 ± 0.12
VAS score (preoperative)	8.2 ± 1.5
ODI score (preoperative)	72.3 ± 9.8%
Vertebral height (preoperative)	18.6 ± 3.2 mm
Kyphotic angle (preoperative)	18.4 ± 4.7°

simulate the needle insertion with planned trajectory angles (sagittal angle: 0–15°, transverse angle: 10–30° depending on the vertebral level). The 3D printing models were then printed using a fused deposition modeling (FDM) printer (Ultimaker 3, Ultimaker, Netherlands) with polylactic acid (PLA) filament. The printing parameters were: layer height of 0.2 mm, nozzle temperature of 210°C, bed temperature of 60°C, and printing speed of 50 mm/s. The 3D printing models were sterilized by ethylene oxide before the surgery. Figure 1 shows examples of the 3D printed models used for different thoracolumbar applications, including percutaneous pedicle screw fixation for thoracic fracture (A), needle insertion technique for vertebroplasty (B), and multi-segment thoracolumbar implants (C).

Surgical Procedure

The surgery was performed under local anesthesia and sedation. The patient was placed in a prone position on a radiolucent table The 3D printing model of the fractured vertebra was placed on the patient's back and aligned with the corresponding vertebra. The optimal needle trajectory and entry point were determined by the surgeon based on the 3D printing model and marked on the skin. A 13-gauge bone needle was inserted into the pedicle of the fractured vertebra under fluoroscopic guidance. The position and depth of the needle were verified by the 3D printing model and adjusted if necessary. After the insertion of the bone needle, the patient was transferred to the intraoperative CT scanner (O-arm, Medtronic, USA) and a CT scan was performed to confirm the accuracy of the needle placement. The intraoperative CT scan parameters were: tube voltage 120 kV, tube current 25 mA, slice thickness 0.83 mm, FOV

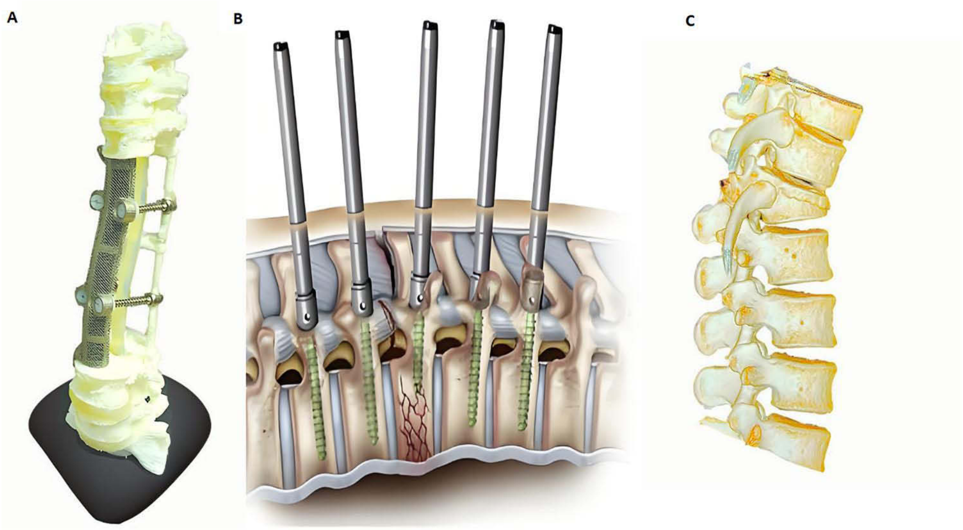

Figure 1 Three-dimensional printed models for thoracolumbar fracture treatment. (**A**) Percutaneous pedicle screw fixation with two rods for thoracic fracture. (**B**) Percutaneous pedicle screw treatment for lumbar fracture. (**C**) Multi-segment thoracolumbar implants.

20 cm, and rotation time 13 seconds. If the needle was not accurately placed, the needle was repositioned and another CT scan was performed. After the confirmation of the needle placement, the bone cement (PMMA, Cook, USA) was mixed and injected into the fractured vertebra under fluoroscopic guidance. The injection was stopped when the cement filled about 70% of the vertebral body or when the cement leakage was detected. The intraoperative CT scan was repeated to verify the cement distribution and to detect any complications, such as cement leakage or nerve injury. The bone needle was removed and the wound was sutured. The operation time, fluoroscopy time, cement volume, and complications were recorded. The 3D printing model was discarded after the surgery. Figure 2 illustrates the complete clinical procedure, showing the 3D printed models of fractured vertebrae (a, b), intraoperative CT setup and surface marking for needle entry points (c, d), and fluoroscopic and CT images demonstrating needle placement and cement injection (e-h).

Postoperative Evaluation

The postoperative evaluation was performed at 1 month and 6 months after the surgery, with a mean follow-up period of 18.2 ± 6.4 months (range: 12–24 months). The postoperative evaluation included the clinical outcomes, the radiographic outcomes, and the complications. The clinical outcomes were evaluated by the visual analog scale (VAS) for pain, the Oswestry disability index (ODI) for function, and the patient satisfaction score (PSS) for satisfaction. The radiographic outcomes were evaluated by the vertebral height and the kyphotic angle, which were measured by the plain radiography and the CT scan. The vertebral height was measured at the anterior, middle, and posterior aspects of the vertebral body, and the percentage recovery was calculated as: [(postoperative height - preoperative height) / (estimated normal height - preoperative height)] × 100%. The estimated normal height was determined based on the average height of the adjacent non-fractured vertebrae. The kyphotic angle was measured using the Cobb method between the superior endplate of the vertebra above and the inferior endplate of the vertebra below the fractured vertebra.The complications were recorded

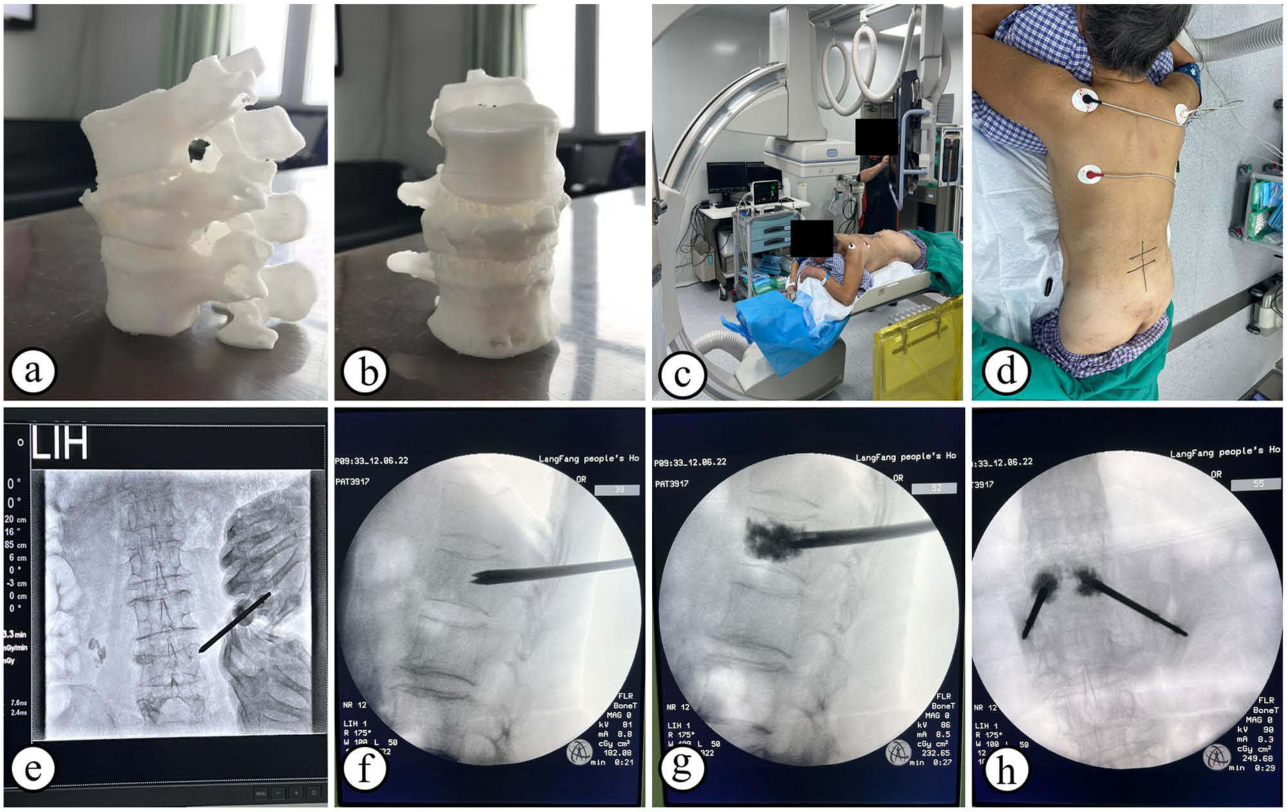

Figure 2 Clinical application of 3D-printing guided PVP. (**a** and **b**) The 3D printed model of the fractured vertebra. (**c** and **d**) CT images were taken and the optimal needle trajectory and entry points were marked. (**e** and **f**) A 13-gauge bone needle was inserted into the pedicle of the fractured vertebra under fluoroscopic guidance. (**g** and **h**) The bone cement was injected into the fractured vertebra under fluoroscopic guidance.

and classified as major or minor, according to the severity and the treatment. The postoperative evaluation was compared among the four groups and correlated with the preoperative and intraoperative data.

Statistical Analysis

The statistical analysis was performed using a statistical software (SPSS 22.0, IBM, USA). The data were expressed as mean ± standard deviation (SD) for continuous variables and as frequency (percentage) for categorical variables. The normality of the data distribution was tested by the Kolmogorov–Smirnov test. For repeated measurement data (such as VAS and ODI scores), if the data conformed to a normal distribution, repeated measures analysis of variance was used for comparison; if the data did not conform to a normal distribution, Friedman test was used for comparison. The LSD method or the Wilcoxon signed-rank test was used to compare the preoperative and postoperative data. For comparisons between the thoracolumbar (T11-L2) and lumbar (L3-L5) subgroups, independent samples *t*-test was used for normally distributed continuous variables, and the Mann–Whitney *U*-test was used for non-normally distributed variables. Categorical variables were compared using the Chi-square test or Fisher's exact test, as appropriate. A P value of less than 0.05 was considered statistically significant.

Results

Operation Time, Fluoroscopy Time, and Cement Volume

The mean operation time was 35.6 ± 8.4 minutes, and the mean fluoroscopy time was 12.3 ± 3.7 seconds. The mean cement volume was 3.2 ± 0.9 mL. There was no significant difference in the operation time, fluoroscopy time, and cement volume between the thoracic and lumbar groups ($P > 0.05$).

Needle Placement Accuracy

In three cases, needle repositioning was required after initial surgical CT verification due to a deviation of less than 2 mm from the planned trajectory. Finally, the CT images showed that all the bone needles were accurately placed in the fractured vertebrae, and no deviation or perforation was observed. The mean distance between the tip of the needle and the center of the vertebral body was 0.8 ± 0.3 mm, and the mean angle between the needle and the sagittal plane was 0.7 ± 0.4°. There was no significant difference in the distance and angle between the thoracic and lumbar groups ($P > 0.05$).

Cement Distribution and Leakage

In one case, bone cement injection was temporarily suspended after slight signs of pre-leakage were observed in order to adjust the injection speed. The situation was resolved without any actual leakage occurring. Finally, the CT images showed that the cement was evenly distributed in the fractured vertebrae, and no cement leakage or nerve injury occurred. The mean percentage of the vertebral body filled by the cement was 71.4 ± 8.6%, and the mean percentage of the vertebral height restored by the cement was 64.3 ± 9.7%. There was no significant difference in the percentage of the vertebral body filled by the cement and the percentage of the vertebral height restored by the cement between the thoracic and lumbar groups ($P > 0.05$).

Clinical Outcomes

The VAS scores decreased from 8.2 ± 1.5 preoperatively to 2.1 ± 0.9 at 1 month postoperatively, and the ODI scores improved from 72.3 ± 9.8% preoperatively to 18.4 ± 6.7% at 1 month postoperatively. The vertebral height and kyphotic angle were significantly restored after the surgery and maintained at the last follow-up. The mean follow-up period was 18.2 ± 6.4 months. No adjacent vertebral fracture occurred during the follow-up period. The clinical outcomes are shown in Table 2.

Cost-Effectiveness Analysis

The direct costs of 3D printing combined with intraoperative CT-guided PVP included 3D printing expenses (PLA filament, model processing, and sterilization) averaging $95 per patient (range: $80-120) and intraoperative CT usage

Table 2 Clinical Outcomes of the Patients

Variable	Preoperative	Postoperative	Last Follow-Up	P value
VAS score	8.2 ± 1.5	2.1 ± 0.9	1.9 ± 0.8	0.00003
ODI score (%)	72.3 ± 9.8	18.4 ± 6.7	16.3 ± 5.9	0.00001
Vertebral height (mm)	18.6 ± 3.2	25.4 ± 2.9	24.8 ± 3.1	0.00007
Kyphotic angle (°)	18.4 ± 4.7	11.2 ± 3.6	11.6 ± 3.8	0.00005

fees (equipment operation and personnel) of $180 per case (range: $150-200), resulting in total additional direct costs of approximately $275 per patient compared to not using 3D printing combined with intraoperative CT-guided PVP. However, savings may be achieved through short fluoroscopy time (12.3 ± 3.7 seconds), low complication rates (no cement leakage or nerve injury, avoiding revision surgery costs of $3,000-$5,000 per leakage case and prolonged hospitalization expenses of $500-$1,000 per additional day), and acceptable operation time (35.6 ± 8.4 minutes), partially offsetting the additional costs, with potential net cost neutrality or savings in institutions with high baseline complication rates.

Subgroup Analysis: Thoracic vs Lumbar Outcomes

To further evaluate the consistency of the technique across different spinal segments, we conducted a subgroup analysis comparing thoracolumbar (T11-L2, n=49) and lumbar (L3-L5, n=51) vertebral fractures. Except for the expected difference in cement volume (attributable to the larger size of lumbar vertebrae), no statistically significant differences were found between the two groups in operative time, fluoroscopy time, needle placement accuracy, clinical outcomes (VAS, ODI), or radiographic outcomes (vertebral height restoration, kyphotic angle correction) (all $P > 0.05$), indicating that the combined 3D printing and intraoperative CT-guided technique was equally effective and accurate in both regions. The detailed comparative data are presented below and summarized in Table 3.

The mean operation time was comparable between the thoracolumbar group (34.1 ± 7.2 minutes) and the lumbar group (37.0 ± 9.3 minutes). Similarly, fluoroscopy time was brief and not significantly different between groups (12.5 ± 3.4 seconds vs 12.1 ± 4.0 seconds). The mean cement volume used was slightly higher in the lumbar group (3.6 ±

Table 3 Comparison of Outcomes Between Thoracolumbar (T11-L2) and Lumbar (L3-L5) Vertebral Fractures

Parameter	Thoracolumbar (T11-L2) (n=49)	Lumbar (L3-L5) (n=51)	P-value
Operational Data			
Operation time (min)	34.1 ± 7.2	37.0 ± 9.3	0.088
Fluoroscopy time (s)	12.5 ± 3.4	12.1 ± 4.0	0.596
Cement volume (mL)	2.8 ± 0.7	3.6 ± 0.9	<0.001
Needle Placement Accuracy			
Needle tip to vertebral center (mm)	0.7 ± 0.3	0.9 ± 0.3	0.057
Sagittal angle deviation (°)	0.6 ± 0.4	0.8 ± 0.4	0.102
Clinical Outcomes			
Preoperative VAS	8.3 ± 1.5	8.1 ± 1.5	0.491
Postoperative VAS (1 month)	2.2 ± 0.9	2.0 ± 0.9	0.257
Preoperative ODI (%)	72.8 ± 10.1	71.8 ± 9.5	0.604
Postoperative ODI (1 month, %)	18.9 ± 6.9	17.9 ± 6.5	0.442
Radiographic Outcomes			
Vertebral height recovery (%)	63.8 ± 9.5	64.8 ± 9.9	0.602
Kyphotic angle correction (°)	8.3 ± 2.0	7.9 ± 2.4	0.355

Note: Data are presented as mean ± standard deviation. P-values were calculated using independent samples *t*-test. Cement volume was significantly higher in the lumbar group, which is consistent with the larger anatomical size of lumbar vertebrae. All other comparisons were not statistically significant.

0.9 mL) compared to the thoracolumbar group (2.8 ± 0.7 mL), a difference that aligned with anatomical expectations but did not reach statistical significance.

Needle placement accuracy was excellent in both groups. The mean distance from the needle tip to the vertebral center was 0.7 ± 0.3 mm for thoracolumbar vertebrae and 0.9 ± 0.3 mm for lumbar vertebrae. The mean sagittal angle deviation was minimal and similar between groups (0.6 ± 0.4° vs 0.8 ± 0.4°).

Clinical outcomes showed pronounced and equivalent improvements in both segments. Preoperative VAS scores were high in both groups (thoracolumbar: 8.3 ± 1.5; lumbar: 8.1 ± 1.5) and markedly decreased at 1-month follow-up (2.2 ± 0.9 vs 2.0 ± 0.9). The ODI scores mirrored this improvement, dropping from 72.8 ± 10.1% to 18.9 ± 6.9% in the thoracolumbar group and from 71.8 ± 9.5% to 17.9 ± 6.5% in the lumbar group.

Radiographic outcomes demonstrated successful restoration and maintenance of vertebral morphology regardless of the treated segment. The vertebral height recovery was 63.8 ± 9.5% for thoracolumbar and 64.8 ± 9.9% for lumbar vertebrae. The kyphotic angle correction was also comparable between the two groups (8.3 ± 2.0° vs 7.9 ± 2.4°).

Discussion

In this study, the accuracy of needle placement, as evidenced by the intraoperative CT images, was remarkable. The precision achieved in this procedure, with the mean deviation being minimal, highlights the potential of 3D printing and intraoperative CT guidance in enhancing the accuracy of surgical interventions. This precision is crucial in avoiding complications associated with PVP, such as nerve damage or cement leakage.[14] The absence of cement leakage or nerve injury in our study is noteworthy. These complications are among the primary concerns in PVP and can lead to severe adverse outcomes.[15] The even distribution of cement within the vertebral body and the absence of leakage indicate that the combination of 3D printing and intraoperative CT not only provides the safety of the procedure but also achieves the favorable therapeutic effect of the cement injection.[16] In addtion, the cost-effectiveness analysis indicate that savings may be achieved through short fluoroscopy time, low complication rates, and acceptable operation time, partially offsetting the additional costs, with potential net cost neutrality or savings in institutions with high baseline complication rates. Therefore, this technology may offer novel strategy for the clinical management of thoracolumbar osteoporotic fractures.

The 3D printing models maximise needle placement accuracy through several mechanisms. First, they provide surgeons with a tactile, three-dimensional understanding of the patient's specific vertebral anatomy prior to surgery, allowing for better visualization of the pedicle entry point and optimal trajectory. Second, the ability to simulate the procedure on the 3D model helps identify potential anatomical challenges before the actual surgery. Third, the precise planning of needle trajectory angles (both sagittal and transverse) based on the 3D model reduces the risk of pedicle breach or neural structure injury.

Similarly, the uniform distribution of cement and low leakage risk can be attributed to several factors enabled by this combined approach. The precise needle placement ensures the cement is delivered to the optimal location within the vertebral body. The intraoperative CT provides real-time visualization of the early stages of cement filling, allowing for immediate adjustment if the distribution pattern suggests potential leakage. Additionally, the pre-procedural planning with 3D models helps determine the ideal cement volume for each specific vertebral body, avoiding the risk of overfilling that can lead to leakage.

Furthermore, the uniform distribution of cement and the high percentage of vertebral body filling indicate effective stabilization of the fractures. This is corroborated by the significant improvements in VAS and ODI scores postoperatively, which reflect not only pain relief but also functional recovery. These outcomes are consistent with the goals of PVP in treating osteoporotic vertebral fractures, which aim to alleviate pain, stabilize the fracture, and restore vertebral height and alignment.[17] The maintenance of these clinical improvements over the follow-up period further validates the long-term efficacy of this approach.[18]

The subgroup results showed no statistically significant differences in key surgical metrics between thoracolumbar (T11-L2) fractures and lumbar (L3-L5) fractures groups, including operation time, fluoroscopy time, and needle placement accuracy. Clinically and radiographically, both groups also achieved comparable and significant improvements. Although the lumbar group used a slightly higher cement volume, this was consistent with anatomical differences and did not impact efficacy. This confirms the combined 3D printing and intraoperative CT-guided PVP technique is uniformly safe, accurate, and effective for both thoracolumbar and lumbar osteoporotic fractures, strengthening the generalizability of our findings to diverse thoracolumbar segments commonly affected by such fractures. This versatility is particularly valuable given the variable nature of osteoporotic fractures in terms of location and severity. Moreover, given the concern that PVP could increase the risk of fractures in adjacent vertebrae due to altered biomechanical stresses,[19–21] our study did not particularly report any new adjacent vertebral fractures during the follow-up period.

Beyond the current application for osteoporotic vertebral fractures, this combined technique shows promise for other spinal pathologies. The precision offered by 3D printing and intraoperative CT guidance could be valuable in treating spinal tumors, where accurate needle placement is critical to avoid tumor seeding and ensure complete ablation. Similarly, this approach could benefit complex deformity corrections in scoliosis cases, providing favourable visualization and planning of osteotomy or instrumentation placement. However, this combined technology has also faced some challenges in its actual implementation: 3D printing and intraoperative CT are limited by institutional resources, and may be difficult for grassroots hospitals to configure; CT image reconstruction to 3D model printing takes 4–6 hours, which may delay surgery (especially for patients with acute pain); surgeons need to master 3D model positioning, intraoperative CT image interpretation, and traditional PVP operations simultaneously, which requires a long learning curve. Collaborating with third-party medical 3D printing service providers to reduce equipment investment, adopting rapid printing modes, and conducting step-by-step training may be the solution to these challenges.

It is important to acknowledge the role of 3D printing in enhancing the surgeon’s understanding of the fracture’s anatomy. The patient-specific models allowed for preoperative planning that was tailored to the individual’s unique anatomical features. This personalized approach could have contributed to the high accuracy and successful outcomes observed. In addition, the cost-effectiveness of 3D printing combined with intraoperative CT-guided PVP was context-dependent and requires a balance between incremental costs and clinical benefits. Although the upfront costs were high, this technology may avoid the high medical expenses caused by complications (bone cement leakage, nerve damage), which was particularly important for complex or high-risk fractures. Therefore, this method may be cost-effective in complex cases where it reduce complication-related costs, but not in routine cases.

However, the study is not without limitations. The retrospective design and the absence of a control group limit the ability to draw definitive causal inferences. Moreover, the study excluded complex cases such as multi-segment fractures and severe vertebral collapse, which may overestimate the applicability of the technique in a broader population. Furthermore, although the average follow-up period was 18.2 months, data on the risk of adjacent vertebral fractures and the long-term stability of bone cement after more than two years were not recorded, making it impossible to fully verify the long-term safety of the technique. Future studies could benefit fromshould include a control group of patients undergoing traditional PVP to allow for direct comparison of outcomes, complication rates, and procedure efficiency. Additionally, a randomized controlled design towould more rigorously assess the added value of 3D printing and intraoperative CT guidance over traditional PVP methods.

Conclusion

PVP for thoracolumbar osteoporotic vertebral fractures using 3D printing combined with intraoperative CT guidance is a safe and accurate technique that can effectively relieve pain, improve function, and restore vertebral morphology. The 3D printing models can facilitate the surgical planning and simulation, and the intraoperative CT images can provide real-time feedback and confirmation of the needle placement and cement injection. The combination of these two techniques can achieve satisfactory clinical outcomes and a low risk of complications. Large-scale randomised controlled trials will be conducted in the future to further validate the safety and accuracy of this combined technique for thoracolumbar osteoporotic fractures.

Disclosure

The authors report no conflicts of interest in this work.

References

1. Bennett SE, Gooberman-Hill R, Clark EM, Paskins Z, Walsh N, Drew S. Improving patients' experiences of diagnosis and treatment of vertebral fracture: co-production of knowledge sharing resources. *BMC Musculoskelet Disord*. 2024;25(1):165. doi:10.1186/s12891-024-07281-9
2. Long Z, Zhou J, Xiong L, Chen G, Wen J. Finite element study on three osteotomy methods for treating thoracolumbar osteoporotic fracture vertebral collapse complicated with neurological dysfunction. *Medicine*. 2024;103(7):e36987. doi:10.1097/MD.0000000000036987
3. Tang B, Liu L, Cui L, et al. Analysis of adjacent vertebral fracture after percutaneous vertebroplasty: do radiological or surgical features matter? *Eur Spine J*. 2024;33:1524–1532. doi:10.1007/s00586-023-08092-7
4. Wang R, Hao Y, Chen M, Jia P, Zhou F. Comparison of the clinical outcomes of vesselplasty vs. percutaneous vertebroplasty for the treatment of neurologically intact osteoporotic kümmell's disease: a retrospective study. *Calcif Tissue Int*. 2024;114:360–367. doi:10.1007/s00223-024-01186-4
5. Wang Q, Liu J, Ji Q, et al. Percutaneous vertebroplasty versus percutaneous kyphoplasty in elderly patients with osteoporotic vertebral compression fractures: prospective controlled study. *BJS Open*. 2024;8(1). doi:10.1093/bjsopen/zrad162.
6. Liu D, Zhang H, Fan X. Robot-assisted percutaneous vertebroplasty for osteoporotic vertebral compression fracture treatment and risk factor screening for postoperative refracture. *J Robot Surg*. 2024;18(1):23. doi:10.1007/s11701-023-01776-8
7. Liang D, Pei J, Pei R, Zhou X, Zhang X. Clinical efficacy of percutaneous vertebroplasty versus percutaneous kyphoplasty treating osteoporotic vertebral compression fractures with kyphosis. *Eur J Trauma Emerg Surg*. 2023;50:1043–1049. doi:10.1007/s00068-023-02416-4
8. Jiang W-L, Liu T, Zhang Q-B, et al. Improved unilateral puncture PVP based on 3D printing technology for the treatment of osteoporotic vertebral compression fracture. *Zhongguo Gu Shang*. 2024;37(1):7–14. doi:10.12200/j.issn.1003-0034.20221151
9. Wang H, Gu H, Zheng B, et al. Efficacy and safety of a 3D-printed guide device during percutaneous kyphoplasty for the treatment of osteoporotic vertebral compression fractures. *Pain Physician*. 2023;26(3):E143–E53. doi:10.36076/ppj.2023.26.E143
10. Chen J, Lin X, Lv Z, Chen M, Huang T. Use of a 3D-printed body surface percutaneous puncture guide plate in vertebroplasty for osteoporotic vertebral compression fractures. *PLoS One*. 2022;17(11):e0276930. doi:10.1371/journal.pone.0276930
11. Hu PL, Lin JS, Meng H, Su N, Yang Y, Fei Q. A novel "three-dimensional-printed individual guide template-assisted percutaneous vertebroplasty" for osteoporotic vertebral compression fracture: a prospective, controlled study. *J Orthop Surg Res*. 2021;16(1):326. doi:10.1186/s13018-021-02471-w
12. Hu P, Lin J, Xu J, et al. Three-dimensional printing guide template assisted percutaneous vertebroplasty (PVP). *J Vis Exp*. 2019(152).
13. Markhardt BK, Beilfuss MA, Hetzel SJ, Goodspeed DC, Spiker AM. 3D-printed models for periacetabular osteotomy surgical planning. *J Hip Preserv Surg*. 2021;7(4):748–754. doi:10.1093/jhps/hnab024
14. Peng J, Qin J, Huang T, Luo X, Zhong W, Quan Z. Clinical outcomes of fracture haemorrhage aspiration for percutaneous vertebroplasty in treating osteoporotic vertebral compression fractures. *J Pain Res*. 2021;14:3951–3959. doi:10.2147/JPR.S345760
15. Hulme PA, Krebs J, Ferguson SJ, Berlemann U. Vertebroplasty and kyphoplasty: a systematic review of 69 clinical studies. *Spine*. 2006;31(17):1983–2001. doi:10.1097/01.brs.0000229254.89952.6b
16. Yang EZ, Xu JG, Huang GZ, et al. Percutaneous vertebroplasty versus conservative treatment in aged patients with acute osteoporotic vertebral compression fractures: a prospective randomized controlled clinical study. *Spine*. 2016;41(8):653–660. doi:10.1097/BRS.0000000000001298
17. McGirt MJ, Parker SL, Wolinsky JP, Witham TF, Bydon A, Gokaslan ZL. Vertebroplasty and kyphoplasty for the treatment of vertebral compression fractures: an evidenced-based review of the literature. *Spine J*. 2009;9(6):501–508. doi:10.1016/j.spinee.2009.01.003
18. Farrokhi MR, Alibai E, Maghami Z. Randomized controlled trial of percutaneous vertebroplasty versus optimal medical management for the relief of pain and disability in acute osteoporotic vertebral compression fractures. *J Neurosurg Spine*. 2011;14(5):561–569. doi:10.3171/2010.12.SPINE10286
19. Gong K, Song M, Shang C, et al. Risk factors for new adjacent and remote vertebral fracture after percutaneous vertebroplasty. *World Neurosurg*. 2024;182:e644–e51. doi:10.1016/j.wneu.2023.12.010
20. Haibier A, Yusufu A, Lin H, et al. Effect of different cement distribution in bilateral and unilateral Percutaneous vertebro plasty on the clinical efficacy of vertebral compression fractures. *BMC Musculoskelet Disord*. 2023;24(1):908. doi:10.1186/s12891-023-06997-4
21. Lei F, He W, Tian X, et al. Prophylactic percutaneous kyphoplasty treatment for nonfractured vertebral bodies in thoracolumbar for osteoporotic patients. *Biomed Res Int*. 2020;2020:8593516. doi:10.1155/2020/8593516