


# Efficacy of Percutaneous Vertebroplasty Assisted by a Curved Cement Delivery Guide for Osteoporotic Vertebral Compression Fractures in the Elderly

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**Objective:** To explore the clinical efficacy of percutaneous vertebroplasty (PVP) assisted by a curved bone cement delivery guide for osteoporotic vertebral compression fractures (OVCFs) in the elderly.

**Methods:** This retrospective cohort study enrolled 96 elderly patients with OVCFs who underwent PVP. Patients were divided into three groups based on the surgical approach: the Curved Guide group (n=34), the Unilateral group (n=30), and the Bilateral group (n=32). Baseline characteristics were compared among the three groups. Surgical parameters assessed included operative time, intraoperative blood loss, and fluoroscopy frequency. Bone cement-related outcomes encompassed injection volume, distribution pattern, and leakage rate. Treatment efficacy was evaluated using VAS and ODI scores. Radiographic outcomes included vertebral height restoration and kyphotic angle correction.

**Results:** Baseline data were comparable among the three groups ( $P > 0.05$ ). The operation time, intraoperative blood loss, and fluoroscopy frequency in the Curved group were significantly lower than those in the Bilateral group ( $P < 0.001$ ) and comparable to those in the Unilateral group ( $P > 0.05$ ). The excellent and good rate of bone cement distribution, vertebral height restoration rate, and Cobb angle correction rate in the Curved group were significantly higher than those in the Unilateral group ( $P < 0.001$ ) and did not differ significantly from those in the Bilateral group ( $P > 0.05$ ). Postoperative improvements in VAS and ODI scores were significantly greater in the Curved group than in the Unilateral group ( $P < 0.05$ ). The incidence of complications was comparable among the three groups ( $P > 0.05$ ).

**Conclusion:** Curved guide-assisted PVP combines the benefits of a minimally invasive unilateral puncture with effective fracture reduction and optimal bone cement distribution. This technique achieves definitive clinical efficacy in elderly patients with OVCFs and merits broader clinical application.

**Keywords:** elderly, PVP, OVCFs, unilateral percutaneous vertebroplasty, percutaneous curved vertebroplasty

## Introduction

Osteoporotic vertebral compression fractures (OVCFs) are a common condition among the elderly population. The annual growth rate of the disease is approximately 4%-5%, and the age-standardized incidence rate has exceeded 850 per 100,000 population. This trend clearly indicates that the incidence of OVCFs continues to rise.<sup>1</sup> These fractures mainly result from reduced bone mineral density and increased vertebral fragility due to osteoporosis. They are frequently triggered by minor trauma or routine daily activities and are typically characterized by severe back pain, nerve root compression symptoms, and impaired motor function.<sup>2</sup> Neuropathic pain significantly diminishes patients' quality of life and can lead to limited mobility, muscle atrophy, and prolonged bed rest factors that further exacerbate osteoporosis and elevate the risk of subsequent fractures.<sup>3</sup> It is estimated that 30%–50% of patients with OVCFs experience persistent pain and kyphotic deformity,<sup>2</sup> which substantially limits their ability to perform daily activities and participate in social interactions. Therefore, developing effective and safe treatment strategies remains an urgent clinical priority.

Current clinical management strategies for OVCFs primarily encompass conservative treatment, including bed rest, analgesics, and bracing, as well as minimally invasive surgical procedures. Among these minimally invasive procedures, percutaneous vertebroplasty (PVP) and percutaneous kyphoplasty (PKP) have emerged as mainstream treatment modalities, providing rapid pain alleviation, vertebral height restoration, and kyphotic deformity correction.<sup>4</sup> PVP stabilizes fractured vertebrae via percutaneous injection of bone cement (eg, polymethylmethacrylate [PMMA]), whereas PKP entails balloon dilation to create a cavity before bone cement injection, thereby mitigating the risk of bone cement leakage.<sup>5</sup> Although these techniques can markedly improve short-term pain and functional outcomes, as evidenced by reductions in Visual Analog Scale (VAS) and Oswestry Disability Index (ODI) scores they are associated with several technical limitations. First, our previous studies have confirmed that uneven cement distribution or leakage is a common complication, occurring in up to 15%–20% of cases, which may lead to nerve injury, pulmonary embolism, or adjacent segment fractures.<sup>6</sup> Second, while conventional unilateral PVP is technically straightforward, it often results in asymmetrical cement distribution. This compromises uniform vertebral support and height restoration, thereby increasing the risk of vertebral re-fracture.<sup>7</sup> Some scholars have reported that a modified transverse process-pedicle approach enables a wider puncture angle and a more favorable needle trajectory.<sup>8,9</sup> This technique significantly enhances the diffusion range and symmetric distribution of bone cement in the vertebral body. However, it requires a high level of surgical proficiency, including detailed anatomical knowledge, excellent three-dimensional spatial awareness, and precise puncture technique. The learning curve is relatively steep, and improper manipulation may increase the risks of neurovascular injury and cement leakage. In contrast, bilateral PVP improves cement distribution at the cost of a longer operation time, greater blood loss and radiation exposure, and reduced tolerability among elderly patients.<sup>10</sup> Additionally, overfilling of cement elevates intravertebral pressure, thereby risking new adjacent fractures. Conversely, conservative treatment for severe fractures has limited efficacy and is further complicated by prolonged non-union, which significantly impacts the quality of life in the elderly.<sup>11</sup> These limitations necessitate the optimization of current treatment approaches.

In response to these limitations, modified techniques including curved-guide-assisted PVP, also known as percutaneous curved vertebroplasty (PCVP), have been introduced in recent years. This technique utilizes a curved guidewire or specialized instruments to guide bone cement injection, facilitating more uniform distribution and precise control.<sup>12</sup> Studies indicate that while retaining the minimally invasive advantages of PVP, PCVP can significantly reduce the cement leakage rate (<10%) and improve vertebral height restoration and Cobb angle correction.<sup>13</sup> For instance, randomized controlled trials show PCVP outperforms traditional unilateral PVP in favorable cement distribution rates and functional scores, with comparable operative time and no additional trauma associated with the bilateral approach.<sup>12,13</sup> Another randomized controlled study confirms PCVP reduces the risk of adjacent vertebral fractures and maintains favorable biomechanical stability.<sup>14</sup> However, most existing research has focused on comparing PCVP with traditional methods, lacking a systematic evaluation of different puncture approaches (eg, unilateral vs. bilateral). Moreover, evidence supporting the comprehensive clinical efficacy and broader applicability of curved-guide techniques remains insufficient.<sup>15</sup>

Therefore, this study aims to investigate the clinical efficacy of curved-guide-assisted PVP in the treatment of OVCFs. By comparing surgical parameters, functional recovery, and imaging outcomes among different puncture groups, curved-guide, unilateral, and bilateral. We seek to evaluate its safety and potential for clinical adoption. The findings of this study are expected to provide evidence-based support for optimizing minimally invasive treatment strategies for OVCFs.

## Methods

### Ethical Approval and Informed Consent

This retrospective study was approved by the Ethics Committee of the Fourth Affiliated Hospital of Harbin Medical University (2024-YXLLSC-32). The study was conducted in strict accordance with the Declaration of Helsinki and relevant medical ethical standards. All enrolled participants provided voluntary, written informed consent prior to any data collection.

## Study Design and Participants

### Study Design

This was a retrospective cohort analysis. Clinical data of elderly OVCFs patients meeting the inclusion criteria were collected, and patients were grouped according to the actual surgical method received. Baseline data, surgery-related indicators, efficacy scores, and imaging results of the three groups were compared to evaluate the clinical application value of PVP assisted by a curved bone cement injection guide.

### Study Population

A total of 96 patients with OVCFs who underwent surgical treatment in the Department of Orthopedics, Fourth Affiliated Hospital of Harbin Medical University, from September 2023 to September 2024 were enrolled. They were divided into three groups according to the surgical method: the Curved group (PVP assisted by curved bone cement injection guide, 34 cases), the Unilateral group (unilateral puncture PVP, 30 cases), and the Bilateral group (bilateral puncture PVP, 32 cases).

### Inclusion Criteria

(1) Age  $\geq 65$  years, with osteoporosis confirmed by dual-energy X-ray absorptiometry (DXA) (lumbar spine or hip T-score  $\leq -2.5$ ); (2) Single-segment fresh vertebral compression fracture (course  $\leq 4$  weeks) confirmed by imaging examinations (X-ray, MRI), with fractured vertebrae in the T6-L5 segment; (3) Clinical manifestations of severe pain at the fracture site (VAS score  $\geq 6$ ), limited mobility, and no neurological injury symptoms; (4) Physical condition tolerating PVP surgery, without absolute surgical contraindications.

### Exclusion Criteria

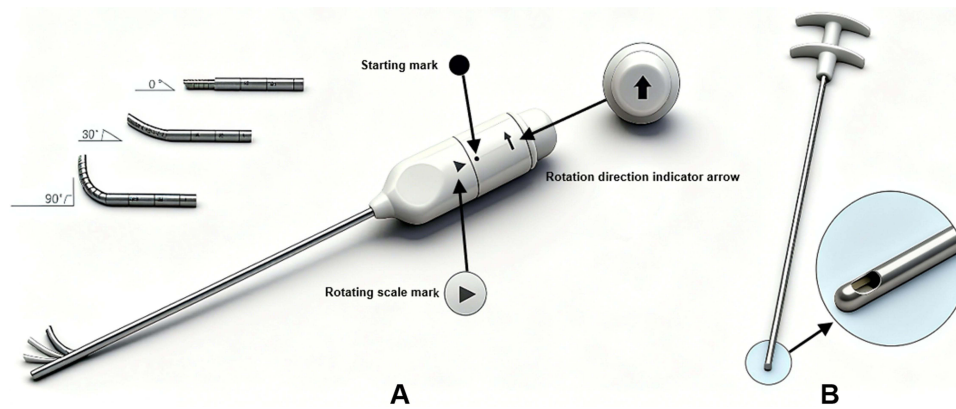
(1) Multiple-segment vertebral fractures, old vertebral fractures (course  $> 4$  weeks), or pathological fractures (eg, caused by tumors or infections); (2) Complications with severe spinal deformity, spinal infection, coagulation disorders, bleeding tendency, or immunocompromise; (3) Allergy to bone cement components (eg, polymethylmethacrylate) or drugs used during surgery; (4) Severe dysfunction of major organs (heart, lung, liver, kidney, etc.) that cannot tolerate surgery or follow-up; (5) Patients with mental illness, cognitive impairment, or inability to cooperate with efficacy evaluation and follow-up; (6) Previous spinal surgery history or surgical history of segments adjacent to the fractured vertebra.

## Surgical Methods and Grouping

To minimize selection bias, patients were assigned to the three groups consecutively based on admission time and the available surgical technique, without any subjective selection based on patient-specific factors. All eligible patients were enrolled consecutively by the same surgical team. Preoperative imaging examinations (X-ray, MRI) were completed to confirm the fracture site, compression degree, and vertebral structure. Prophylactic antibiotics were routinely administered 30 minutes before surgery. All surgeries were performed by the same experienced team of orthopedic surgeons.

### Curved Group (PVP Assisted by Curved Bone Cement Injection Guide)

Patients were placed in the prone position. The fractured vertebra was localized by C-arm fluoroscopy, and the puncture point was marked. Routine disinfection and draping were performed, followed by local infiltration anesthesia with 2% lidocaine up to the peripedicular region. The transpedicular puncture approach was used. The puncture site was marked 1–2 cm lateral to the pedicular outer margin projection, and punctured to the cortical bone at the posterior pedicle margin. Needle direction was adjusted to align with the vertebral midline under biplanar fluoroscopy. The needle was advanced by tapping with repeated localization. When the needle tip reached the posterior vertebral margin and crossed the inner pedicle margin on anteroposterior fluoroscopy, it was further advanced by tapping to the anterior 1/3 of the vertebral body, with the anteroposterior position at the vertebral center. After confirming the correct puncture position, the needle core was withdrawn, and a curved bone cement injection guide was inserted (Figure 1A). A variable-angle guide was used to create multiple cement channels inside the vertebra in various directions to ensure coverage of the vertebral midline area. The prepared bone cement was slowly injected into the vertebra through a lateral-opening bone cement injector during the “stringing stage” (Figure 1B). Real-time fluoroscopy was performed to monitor bone cement distribution, avoiding excessive injection to prevent leakage. Injection



**Figure 1** Product Schematic Diagram. (A) Curved bone cement injection guide product. (B) Lateral opening bone cement injector for vertebroplasty.

was stopped when the bone cement filling was satisfactory or close to the posterior edge of the vertebra. The puncture cannula was withdrawn, the incision was sutured, disinfected with povidone-iodine, and covered with a sterile dressing (Figure 2).

### Unilateral Group (Unilateral Puncture PVP)

Patient position, anesthesia method, and puncture approach were the same as those in the Curved group. After the puncture needle reached the predetermined position, the curved guide was not used. Instead, the “stringing stage” bone cement was slowly injected into the fractured vertebra through the bone cement injection cannula. Fluoroscopy was used to monitor bone cement distribution and prevent leakage. After injection, the puncture needle was withdrawn, and the incision was sutured, disinfected, and dressed (Figure 3).

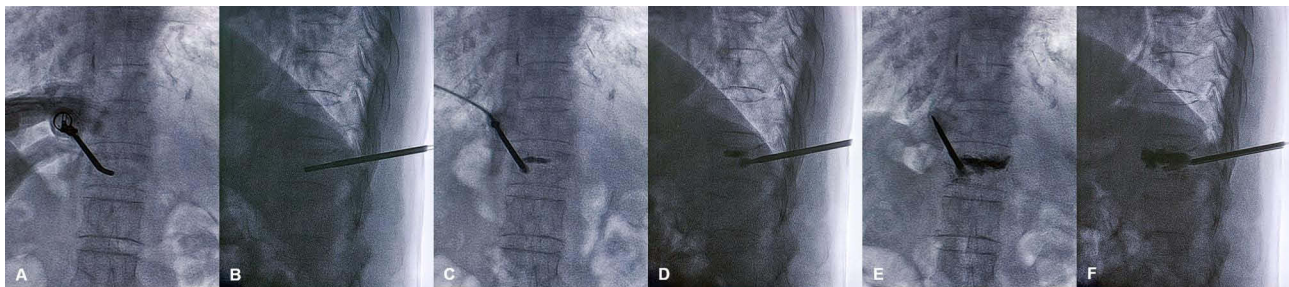
### Bilateral Group (Bilateral Puncture PVP)

Patient position and anesthesia method were the same as above. Puncture points were marked on both pedicles of the fractured vertebra, and bilateral punctures were performed sequentially to ensure both puncture needles reached the anterior-middle 1/3 of the vertebra. “Stringing stage” bone cement was alternately injected bilaterally, and fluoroscopy was used to monitor distribution, ensuring uniform filling on both sides and avoiding excessive unilateral injection. After injection, both puncture needles were withdrawn, the puncture points were sutured, disinfected, and dressed (Figure 4).

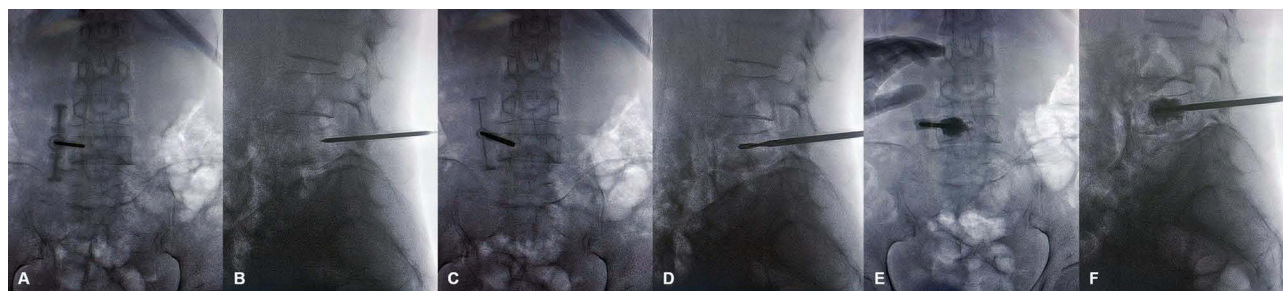
## Data Collection

### Baseline Data Collection

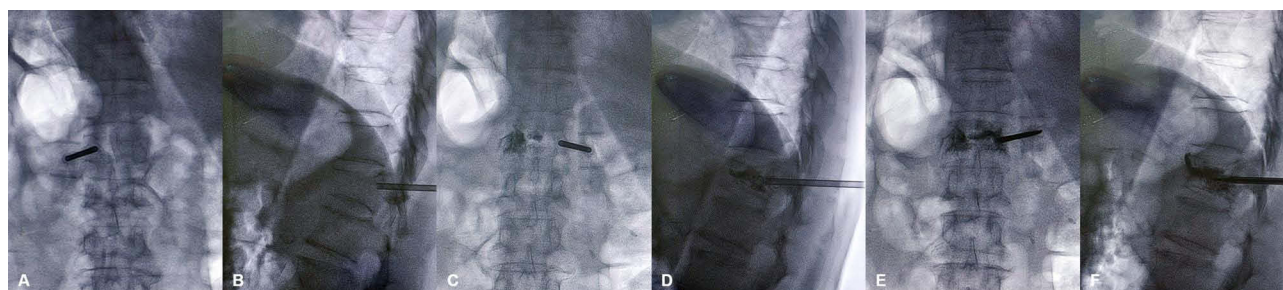
Baseline information was extracted from the electronic medical record system. It included gender, age, body mass index (BMI), bone mineral density (BMD) T-score, fracture site (thoracic vertebra/lumbar vertebra), and history of falls (at the time of fracture). Additional extracted data encompassed the course of disease (time from fracture occurrence to surgery,



**Figure 2** Curved Group: PVP Intraoperative Procedure Flow Chart. (A) Establish bone cement inflow channels in multiple directions inside the vertebral body using the flexible bone cement injector. (B) Insert the bone cement injector into the vertebral body for subsequent cement delivery. (C–F) Intraoperatively, perform real-time anteroposterior (AP) and lateral X-ray fluoroscopy to monitor the injection and distribution of bone cement.



**Figure 3** Unilateral Group: PVP Intraoperative Procedure Flow Chart. (A–C) Under the guidance of AP and lateral X-ray fluoroscopy, the operator establishes a unilateral working channel inside the vertebral body using a puncture handle. (D) Dilate the puncture channel with a drill bit inside the fractured vertebral body. (E and F) Under real-time X-ray monitoring, inject bone cement into the vertebral body.



**Figure 4** Bilateral Group: PVP Intraoperative Procedure Flow Chart. (A and B) Insert the working cannula at the left pedicle of the vertebral body to establish a bone cement injection channel. (C and D) After completing the bone cement injection in the left working channel, insert the working cannula at the right vertebral pedicle to establish a subsequent bone cement injection channel. (E and F) Complete bone cement injection in the right working channel under X-ray fluoroscopy guidance.

categorized as  $<7$  days or  $\geq 7$  days), and fracture compression degree (categorized as  $<1/3$  or  $\geq 1/3$ , determined by the ratio of preoperative anterior vertebral height to normal vertebral height measured via X-ray).

### Surgery-Related Data Collection

Intraoperative data were recorded in real time. These data included operation time (total time from puncture initiation to completion of bone cement injection and puncture needle withdrawal), intraoperative blood loss (estimated by the aspirator-collected amount combined with gauze soaking), intraoperative X-ray fluoroscopy times (cumulative times during the entire operation), and bone cement injection volume (total volume of bone cement actually injected into the vertebra). Postoperative imaging examinations (X-ray or CT within 1 week after surgery) were performed to evaluate bone cement distribution. “Excellent bone cement distribution” was defined as bone cement covering the vertebral midline area or uniformly distributing in the anterior 2/3 of the vertebra without obvious lateral deviation.<sup>16</sup> “Bone cement leakage” was defined as bone cement extending beyond the fractured vertebra (eg, into the spinal canal, paravertebral soft tissues, or venous plexus). Patients were followed up for 1 year, and the occurrence of adjacent vertebral fractures (new compression fractures in the segments adjacent to the fractured vertebra) was documented.

### Efficacy-Related Data Collection

(1) Pain score: The Visual Analog Scale (VAS) was used to assess pain intensity, with a score range of 0–10 (0 = no pain, 10 = severe pain). Scores were self-reported by patients preoperatively, 1 day, 7 days, and 1 month postoperatively.<sup>17</sup> (2) Functional disability score: The Oswestry Disability Index (ODI) was used to evaluate spinal function, including 10 dimensions (pain intensity, self-care, lifting, walking, sitting, standing, sleeping, sexual life, social activities, and traveling). The disability index percentage (%) = (actual score / 50)  $\times$  100%, with a total score of 0–100 (higher scores indicate more severe functional disability). Evaluations were completed preoperatively, 1 day, 7 days, and 1 month postoperatively.<sup>18</sup> (3) Imaging index measurement: Using Picture Archiving and Communication System (PACS) image display software (Neusoft Group, Shenyang, Liaoning, China; Version 7.5), the anterior height of the fractured vertebra and the Cobb kyphotic angle (angle

between the extension lines of the upper and lower endplates of the fractured vertebra) were measured preoperatively and 1 month postoperatively. Based on the measurements, the recovery rate of vertebral height (RRVH) and correction rate of Cobb angle (CACR) were calculated using the following formulas: Recovery rate of vertebral height (RRVH) =  $(b - a) / [(c + d)/2] \times 100\%$ , where  $a$  = preoperative anterior height of the fractured vertebra,  $b$  = postoperative anterior height of the fractured vertebra,  $c$  = anterior height of the normal vertebra above the fractured vertebra,  $d$  = anterior height of the normal vertebra below the fractured vertebra.<sup>19</sup> Correction rate of Cobb kyphotic angle (CACR) =  $(\alpha - \beta)/\alpha \times 100\%$ , where  $\alpha$  = preoperative Cobb angle of the fractured vertebra,  $\beta$  = postoperative Cobb angle of the fractured vertebra (Figure 5).<sup>20</sup>

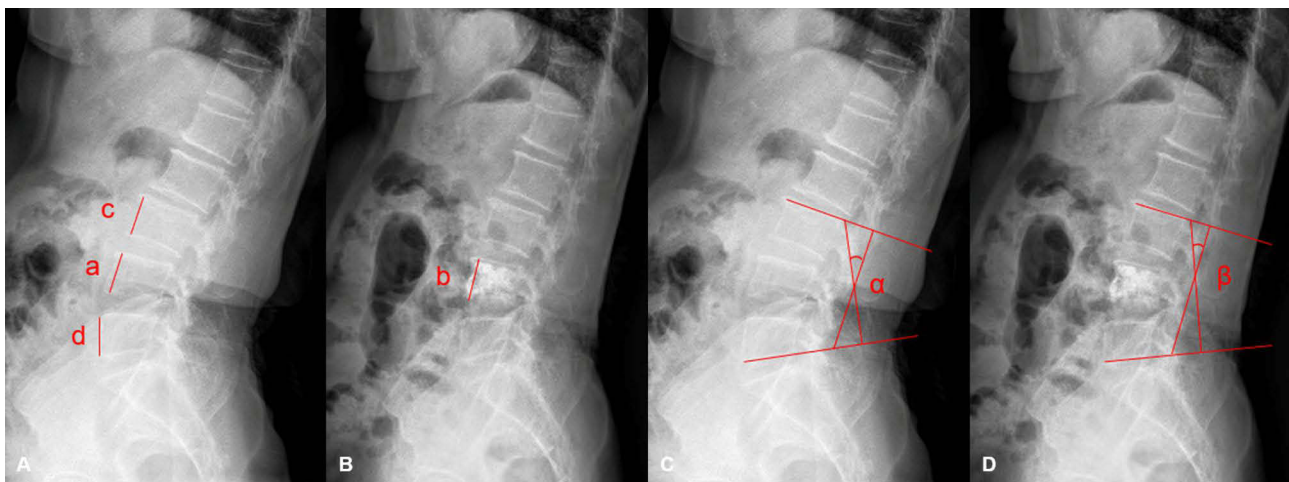
## Statistical Analysis

Statistical analysis was performed using SPSS 25.0 software (IBM, Armonk, NY, USA). Measurement data (eg, age, BMI, BMD, operation time, blood loss, VAS score, ODI score, anterior vertebral height, Cobb angle) were expressed as “mean  $\pm$  standard deviation (mean  $\pm$  SD)”. Normality test (Shapiro–Wilk test) and homogeneity of variance test (Levene test) were performed first. If the data were normally distributed and variances were homogeneous, one-way analysis of variance (one-way ANOVA) was used for overall comparison among the three groups; if normally distributed but with heterogeneous variances, Welch’s ANOVA was used. Pairwise comparisons between groups were performed using  $t$ -tests with Bonferroni correction. Categorical data (eg, gender, course of disease, fracture compression degree, excellent bone cement distribution, bone cement leakage, adjacent vertebral fracture) were expressed as percentages (n/N, %). Overall comparison among the three groups was performed using Pearson’s  $\chi^2$ -test; if there were cells with expected frequencies  $< 5$ , Fisher’s exact test was used. Pairwise comparisons between groups were performed using  $\chi^2$ -tests or Fisher’s exact tests with Bonferroni correction. A  $P$ -value  $< 0.05$  was considered statistically significant.

## Results

### Baseline Data

As shown in Table 1, there were no statistically significant differences in demographic data (gender, age, BMI) and disease-related baseline characteristics (BMD T- score, course of disease, fracture compression degree, fracture site, history of falls) among the three groups ( $P > 0.05$ ). This indicates that the baseline data of the three groups were balanced and comparable, laying a reliable foundation for subsequent comparisons of efficacy and safety.



**Figure 5** RRVH and CCAR Measurement Method Schematic. (A and B) a, anterior height of fracture vertebra (preoperative); b, anterior height of fracture vertebra (postoperative); c, upper adjacent vertebral anterior height; d, lower adjacent vertebral anterior height (preoperative). RRVH =  $(b - a) / [(c + d)/2] \times 100\%$  (C and D)  $\alpha$ , Cobb angle (preoperative);  $\beta$ , Cobb angle (postoperative). CACR =  $(\alpha - \beta) / \alpha \times 100\%$ .

**Table 1** Baseline Characteristics Comparison

Variable	Curved Group (N=34)	Unilateral Group (N=30)	Bilateral Group (N=32)	$\chi^2$ /F	p-value (Curved vs Unilateral)	p-value (Curved vs Bilateral)	p-value (Unilateral vs Bilateral)
Sex (M/F)	9/25 (26.5%)	7/23 (23.3%)	8/24 (25.0%)	$\chi^2= 0.084$	0.923	0.987	0.945
Age (years)	75.53 $\pm$ 7.59	75.17 $\pm$ 7.36	74.91 $\pm$ 7.13	F=0.298	0.847	0.721	0.883
BMI (kg/m <sup>2</sup> )	24.67 $\pm$ 3.70	24.81 $\pm$ 3.86	24.22 $\pm$ 3.82	F=0.245	0.889	0.630	0.553
BMD (T-score)	-3.13 $\pm$ 0.38	-3.16 $\pm$ 0.36	-3.17 $\pm$ 0.38	F=0.321	0.755	0.701	0.941
Duration (< 7days)	21/13 (61.8%)	22/8 (73.3%)	24/8 (75.0%)	$\chi^2= 1.629$	0.474	0.374	0.917
Compression degree (< I/3)	23/11 (67.6%)	19/11 (63.3%)	22/10 (68.8%)	$\chi^2= 0.227$	0.921	0.989	0.856
Fracture location (thoracic/lumbar)	18/16 (52.9%)	16/14 (53.3%)	17/15 (53.1%)	$\chi^2=0.001$	0.992	0.995	0.998
Fall history (yes/no)	12/22 (35.3%)	13/17 (43.3%)	14/18 (43.8%)	$\chi^2= 0.621$	0.688	0.652	0.976

**Notes:** Data are mean  $\pm$  SD or n/N (%). Group comparisons used one-way/Welch's ANOVA (continuous variables) or Pearson's  $\chi^2$ -test (categorical variables).  $P < 0.05$  was considered statistically significant.

## Surgery-Related Indicators

The comparison of surgery-related data is shown in Table 2. Regarding minimally invasive-related indicators, the operation time (26.18  $\pm$  3.01 min), intraoperative blood loss (9.29  $\pm$  2.62 mL), and fluoroscopy times (22.38  $\pm$  2.65 times) in the Curved group were not significantly different from those in the Unilateral group ( $P > 0.05$ ). However, these values in the Curved group were significantly lower than those in the Bilateral group (40.53  $\pm$  2.98 min, 18.41  $\pm$  4.35 mL, 42.16  $\pm$  4.36 times,  $P < 0.001$ ). For bone cement-related indicators, the Curved group showed no significant difference in injection volume (5.29  $\pm$  0.52 mL) or excellent distribution rate (82.4%) compared to the Bilateral group (5.42  $\pm$  0.63 mL, 84.4%,  $P > 0.05$ ). Both values in the Curved group were significantly higher than those in the Unilateral group (2.95  $\pm$  0.30 mL, 30.0%,  $P < 0.001$ ). In terms of safety, there were no statistically significant differences in the incidence of bone cement leakage (8.8% vs. 6.7% vs. 9.4%) and adjacent vertebral fractures (11.8% vs. 10.0% vs. 28.1%) among the three groups ( $P > 0.05$ ).

## Clinical Efficacy (VAS and ODI Scores)

As shown in Table 3, no statistically significant differences were observed in preoperative VAS and ODI scores among the three groups ( $P > 0.05$ ). Postoperatively, all groups exhibited significant improvements in pain relief and functional recovery,

**Table 2** Operative Data Comparison

Variable	Curved Group (N=34)	Unilateral Group (N=30)	Bilateral Group (N=32)	$\chi^2$ /F	p-value (Curved vs Unilateral)	p-value (Curved vs Bilateral)	p-value (Unilateral vs Bilateral)
Operation time (min)	26.18 $\pm$ 3.01	25.77 $\pm$ 3.21	40.53 $\pm$ 2.98	F=198.576	0.600	0.001	0.001
Blood loss (mL)	9.29 $\pm$ 2.62	9.97 $\pm$ 2.51	18.41 $\pm$ 4.35	F=89.347	0.607	0.001	0.001
No. of fluoroscopic views	22.38 $\pm$ 2.65	21.97 $\pm$ 2.31	42.16 $\pm$ 4.36	F=278.451	0.509	0.001	0.001
Bone cement volume (mL)	5.29 $\pm$ 0.52	2.95 $\pm$ 0.30	5.42 $\pm$ 0.63	F=302.168	0.001	0.288	0.001
Favorable cement distribution (yes/no)	28/6 (82.4%)	9/21 (30.0%)	27/5 (84.4%)	$\chi^2=24.514$	0.001	0.803	0.001
Cement leakage (yes/no)	3/31 (8.8%)	2/28 (6.7%)	3/29 (9.4%)	$\chi^2=0.1875$	1.000	1.000	1.000
Adjacent vertebral fracture (yes/no)	4/30 (11.8%)	3/27 (10.0%)	9/23 (28.1%)	$\chi^2= 4.5732$	1.000	0.521	0.414

**Notes:** Data are mean  $\pm$  SD or n/N (%). Group comparisons used one-way/Welch's ANOVA (continuous variables) or Pearson's  $\chi^2$ /Fisher's exact test (categorical variables).  $P < 0.05$  was considered statistically significant.

**Table 3** Efficacy Outcomes (VAS and ODI)

Variable	Curved Group (N=34)	Unilateral Group (N=30)	Bilateral Group (N=32)	F	p-value (Curved vs Unilateral)	p-value (Curved vs Bilateral)	p-value (Unilateral vs Bilateral)
VAS (preop)	7.21 ± 0.87	7.14 ± 0.82	7.09 ± 0.79	0.18	0.745	0.568	0.812
VAS (postop 1 day)	3.56 ± 0.91	4.18 ± 0.84	3.34 ± 0.61	9.34	0.005	0.278	0.001
VAS (postop 7 days)	2.44 ± 0.64	3.29 ± 0.71	2.53 ± 0.62	17.89	0.001	0.552	0.001
VAS (postop 1 month)	0.82 ± 0.59	2.14 ± 0.68	0.81 ± 0.62	48.23	0.001	0.934	0.001
ODI (preop)	73.15 ± 5.80	73.39 ± 5.89	74.06 ± 5.41	0.23	0.863	0.512	0.647
ODI (postop 1 day)	35.21 ± 4.81	39.39 ± 6.21	33.59 ± 5.58	12.76	0.003	0.448	0.001
ODI (postop 7 days)	25.18 ± 4.65	30.32 ± 4.79	24.34 ± 3.96	18.34	0.001	0.456	0.001
ODI (postop 1 month)	17.35 ± 3.44	23.89 ± 4.01	17.88 ± 2.75	36.45	0.001	0.527	0.001

Notes: Data are mean ± SD. Group comparisons used one-way/Welch's ANOVA.  $P < 0.05$  was considered statistically significant.

with notable differences between groups. At 1 day, 7 days, and 1 month postoperatively, the Curved group had significantly lower VAS pain scores than the Unilateral group ( $P < 0.05$ ). Meanwhile, the Curved group's VAS scores were not significantly different from those of the Bilateral group at these time points ( $P > 0.05$ ). Consistent with the VAS score trend, the Curved group achieved significantly better functional recovery (assessed by ODI) than the Unilateral group at all postoperative time points ( $P < 0.05$ ). The Curved group's ODI was comparable to that of the Bilateral group ( $P > 0.05$ ).

## Imaging Results

The comparison of imaging indicators is shown in Table 4. Preoperatively, there were no statistically significant differences in the anterior height of the fractured vertebra and Cobb angle among the three groups ( $P > 0.05$ ). Postoperatively: The anterior vertebral height ( $20.81 \pm 2.42$  mm), recovery rate of vertebral height (RRVH,  $26.72 \pm 2.06\%$ ), and correction rate of Cobb angle (CACR,  $67.81 \pm 2.86\%$ ) in the Curved group were not significantly different from those in the Bilateral group ( $21.04 \pm 2.47$  mm,  $26.83 \pm 1.93\%$ ,  $68.52 \pm 2.74\%$ ,  $P > 0.05$ ). The above imaging indicators in the Curved group were significantly superior to those in the Unilateral group ( $18.11 \pm 2.64$  mm,  $18.20 \pm 2.43\%$ ,  $38.19 \pm 4.13\%$ ,  $P < 0.001$ ). The postoperative Cobb angle in the Curved group ( $14.86 \pm 2.44$ ) was significantly smaller than that in the Unilateral group ( $17.61 \pm 2.82$ ,  $P < 0.001$ ) and not significantly different from that in the Bilateral group ( $14.22 \pm 2.33$ ,  $P > 0.05$ ).

**Table 4** Radiological Outcomes

Variable	Curved Group (N=34)	Unilateral Group (N=30)	Bilateral Group (N=32)	F	p-value (Curved vs Unilateral)	p-value (Curved vs Bilateral)	p-value (Unilateral vs Bilateral)
Anterior vertebral height preop (mm)	16.45±2.27	16.92 ± 2.85	16.43±2.42	0.89	0.38	0.59	0.81
Anterior vertebral height postop (mm)	20.81 ± 2.42	18.11 ± 2.64	21.04 ± 2.47	12.34	0.001	0.92	0.001
RRVH (%)	26.72 ± 2.06	18.20 ± 2.43	26.83 ± 1.93	178.11	0.001	0.557	0.001
Cobb angle preop (°)	22.61 ± 3.53	22.81 ± 3.24	22.92 ± 3.63	0.06	0.96	0.643	0.99
Cobb angle postop (°)	14.86 ± 2.44	17.61 ± 2.82	14.22 ± 2.33	16.14	0.001	0.22	0.001
CACR (%)	67.81 ± 2.86	38.19 ± 4.13	68.52 ± 2.74	872.45	0.001	0.39	0.001

Notes: Data are mean ± SD. Group comparisons used one-way/Welch's ANOVA.  $P < 0.05$  was considered statistically significant.

## Discussion

In the elderly, OVCFs are frequently induced by low-energy trauma, which results in neuropathic pain and motor dysfunction, thereby severely compromising patients' quality of life.<sup>21</sup> These fractures cause persistent back pain and may precipitate spinal deformity due to vertebral collapse, aggravating both nerve compression and functional mobility limitations.<sup>22</sup> PVP has become the standard treatment, which can effectively relieve pain and stabilize vertebrae. However, traditional unilateral or bilateral puncture methods have limitations in surgical efficiency, bone cement distribution, and functional recovery.<sup>23</sup> This study focuses on the efficacy analysis of PVP assisted by a curved bone cement injection guide (Curved group). The results show that this technique combines the minimally invasive advantages of unilateral puncture and the distribution effect of bilateral puncture, significantly improving the overall efficacy of OVCFs treatment. It thus offers a new idea for improving neuropathic pain and motor function in elderly patients.

### Core Findings: Surgical Efficacy and Bone Cement Distribution

The results of this study indicate that the Curved group performed excellently in surgery-related indicators, bone cement distribution, and clinical efficacy. Specifically, the operation time ( $26.18 \pm 3.01$  min), intraoperative blood loss ( $9.29 \pm 2.62$  mL), and fluoroscopy times ( $22.38 \pm 2.65$  times) in the Curved group were significantly lower than those in the Bilateral group ( $P < 0.001$ ) and not significantly different from those in the Unilateral group ( $P > 0.05$ ) (Table 2). The curved guide device significantly optimizes surgery by reducing operative trauma and radiation exposure. This is consistent with prior literature: studies indicate that curved guides such as PCVP simplify the puncture path, lower surgical complexity, and shorten operation time, thereby decreasing complication risks.<sup>12</sup> Regarding bone cement-related indicators, the bone cement injection volume ( $5.29 \pm 0.52$  mL) and excellent distribution rate (82.4%) in the Curved group were comparable to those in the Bilateral group ( $P > 0.05$ ) but significantly superior to those in the Unilateral group ( $P < 0.001$ ) (Table 2). This highlights the advantage of the curved guide in ensuring adequate bone cement distribution, which is consistent with existing evidence: the use of curved guide wires or similar techniques can improve the diffusion of bone cement within the vertebra, reduce uneven distribution, and thereby enhance biomechanical stability.<sup>7,24</sup>

### Safety Evaluation of Curved Technique

In terms of safety, there was no significant difference in the incidence of bone cement leakage among the three groups (8.8% vs. 6.7% vs. 9.4%) ( $P > 0.05$ ). Regarding the incidence of adjacent vertebral fractures, although the Curved group (11.8%) and Unilateral group (10.0%) were lower than the Bilateral group (28.1%), the difference was not statistically significant ( $P > 0.05$ ). Larger sample sizes and longer follow-up periods are needed in future studies (Table 2). This indicates that the Curved technique does not increase additional risks, which is consistent with the results of multiple studies: PCVP or curved guidance methods are comparable to traditional methods in terms of leakage and complications (Table 2).<sup>13,14,25</sup> That said, other studies have shown that in severe compression fractures (eg, Genant Type IV), the risk of bone cement leakage rises with increasing compression severity.<sup>26</sup> Leakage rates reach 13.33% in mild fractures and 22.22% in severe cases. This indicates that strict individualized assessment is needed when applying this technique to severe compression fractures, which helps reduce the risk of bone cement leakage.

### Clinical Efficacy and Imaging Reconstruction Effects

The Curved group demonstrated significantly superior postoperative VAS scores and ODI indices compared to the Unilateral group ( $P < 0.001$ ). Additionally, its clinical efficacy was comparable to that of the Bilateral group ( $P > 0.05$ ). This result is directly related to the relief of neuropathic pain: the reduction in VAS scores reflects rapid pain relief, while the improvement in ODI indices indicates the recovery of motor function, such as enhanced ability to perform daily activities (Table 3). Imaging evaluations further confirm this: the recovery rate of anterior vertebral height (RRVH,  $26.72 \pm 2.06\%$ ) and correction rate of Cobb kyphotic angle (CACR,  $67.81 \pm 2.86\%$ ) in the Curved group were not different from those in the Bilateral group ( $P > 0.05$ ) but significantly superior to those in the Unilateral group ( $P < 0.001$ ) (Table 4). This suggests that the curved guide effectively restores vertebral height and spinal alignment by optimizing bone cement distribution, thereby reducing nerve compression and secondary functional disorders. Overall, the Curved technique provides an efficient treatment option for

OVCF patients, significantly improving their quality of life and reducing dependence and limited mobility caused by motor dysfunction through rapid pain relief and functional recovery.

## Comparison with Existing Studies

The advantage of this study lies in the direct comparison of the curved guide technique with traditional methods, confirming that it combines the minimally invasiveness of the Unilateral group and the distribution effect of the Bilateral group. Firstly, the Curved group showed improved surgical efficiency by reducing operation time and radiation exposure ( $P < 0.001$ ) (Table 2). This finding is supported by a meta-analysis. Li et al pointed out that unilateral curved percutaneous vertebral augmentation (PVA) techniques (eg, PCVP) significantly reduce fluoroscopy times and operation time compared with bilateral straight puncture, while maintaining similar safety.<sup>23,27</sup> This improvement in efficiency is particularly important for elderly patients, as it can reduce intraoperative stress and recovery time. Secondly, with respect to bone cement distribution, the high excellent rate (82.4%) in the Curved group was comparable to that in the Bilateral group (84.4%) and much higher than that in the Unilateral group (30.0%) (Table 2). This is consistent with existing literature reports: the use of curved guidance devices can simulate the symmetric distribution of bilateral puncture, avoiding the limitations of the unilateral method. For example, Hu et al confirmed that curved guide wire technology can enhance the uniform diffusion of bone cement within the vertebra, reduce “dead zones”, thereby improving biomechanical support and pain relief.<sup>28</sup> Similarly, Wang et al compared PCVP with bilateral PKP and found no significant differences in bone cement distribution and refracture rate, but PCVP had more minimally invasive advantages.<sup>29</sup>

PCVP technology effectively reduces pain scores and disability indices. This finding, based on VAS and ODI results, aligns with multiple studies regarding clinical efficacy and functional recovery. A retrospective analysis showed that after PCVP treatment for thoracolumbar OVCF, patients’ pain was significantly relieved, and the ODI improvement rate reached over 85%, which was comparable to bilateral puncture.<sup>27</sup> This is attributed to optimized bone cement distribution reducing nerve root irritation and vertebral instability.<sup>30</sup> In addition, the superiority of imaging indicators (eg, 67.81% Cobb angle correction rate) emphasizes the improvement of spinal mechanics by the Curved technique, which is consistent with the study by Li et al: symmetric bone cement distribution can better correct kyphotic deformity and reduce nerve compression-related complications.<sup>31</sup> Safety data from another study showed that the Curved group did not increase the risk of leakage or adjacent fractures, which refutes some controversies: for example, meta-analyses by Sharif and Huang pointed out that PCVP is similar to traditional UVP in terms of complication rates.<sup>13,25</sup>

## Core Innovative Advantages and Clinical Application Value

The core advantage of PVP assisted by a curved bone cement injection guide lies in its innovative design: it combines the low invasiveness of unilateral puncture (reducing bleeding and trauma) with the high distribution efficiency of bilateral puncture, directly targeting the neuropathic pain of OVCF. Pain relief and motor function recovery not only improve short-term quality of life but may also reduce the risk of long-term disability. Compared with existing studies, this technique is similar to other innovative methods, such as directional bone cement technology or curved vertebroplasty, but this study provides more direct evidence for its clinical application through a clear three-group design.<sup>32,33</sup>

## Limitations and Clinical Implications

This study has certain limitations. The sample size was relatively small (96 cases) and this was a single-center retrospective study, which may compromise the generalizability of the findings. Future investigations should expand the sample size and conduct long-term follow-up to assess indicators related to patients’ long-term motor function and quality of life and observe the long-term risk of adjacent vertebral fractures. This study also did not evaluate the impact of material parameters including bone cement elastic modulus on therapeutic efficacy, with subsequent research able to integrate biomechanical simulations to further optimize the guide device design.

Despite rigorous control measures applied during study design and data analysis, this retrospective cohort study was inevitably affected by potential confounding variables. Preoperative CT examination was not routinely performed in all patients, which prevented systematic confirmation of vertebral wall integrity and comprehensive screening for intravertebral lesions, including Kummell’s disease and the basivertebral foramen sign. Minor individual variations in intraoperative

procedures (eg, bone cement injection speed and the range of puncture angle adjustment) may also influence the distribution of bone cement within the vertebral body and the incidence of cement leakage, thereby potentially affecting surgical outcomes and final clinical efficacy. In addition, the follow-up period of this study was relatively short, and the potential confounding effects of long-term postoperative factors (eg, patients' compliance with standardized anti-osteoporosis treatment, nutritional status, and the implementation of fall prevention interventions) on the risk of adjacent vertebral fractures and patients' long-term spinal functional recovery have not been fully assessed. Meanwhile, PCVP remains an emerging minimally invasive surgical technique that has not yet been widely and standardly promoted and applied in clinical practice, and its clinical popularity and technical standardization still need to be further improved.

## Conclusion

In conclusion, curved bone cement injection guide-assisted PVP exhibits significant advantages in OVCF treatment, including high surgical efficiency, excellent bone cement distribution, remarkable clinical efficacy, and controllable safety. Compared with traditional methods, its comprehensive performance makes it a preferred strategy for elderly OVCF patients. Unilateral local anesthesia puncture reduces intraoperative pain, rendering it particularly suitable for elderly individuals with multiple comorbidities and high surgical risks.

## Abbreviations

PVP, percutaneous vertebroplasty; OVCF, osteoporotic vertebral compression fractures; PKP, percutaneous kyphoplasty; VAS, visual analog scale; ODI, Oswestry disability index; PCVP, percutaneous curved vertebroplasty; UVP, unilateral percutaneous vertebroplasty; DXA, dual-energy X-ray absorptiometry; BMI, body mass index; BMD, bone mineral density; RRVH, recovery rate of vertebral height; CACR, correction rate of Cobb angle; PVA, percutaneous vertebral augmentation.

## Data Statement

All original data are available upon reasonable request to the corresponding authors.

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## Disclosure

The authors report no conflicts of interest in this work.

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