

Modified Percutaneous Vertebroplasty with Bilateral Cannulated Screws and Staged Cement Injection for Stage I and II Kummell's Disease: A Mid-to-Long Term Follow-Up Study

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Abstract

Background

Kummell's disease (KD) is a delayed post-traumatic vertebral osteonecrosis often complicated by intravertebral vacuum cleft (IVC), cement loosening, and progressive vertebral collapse after conventional percutaneous vertebroplasty (PVP) or kyphoplasty. This study introduces a modified PVP technique using bilateral cannulated screws and staged cement injection for stage I and II KD, and evaluates its safety, feasibility, and mid-to-long-term clinical and radiological outcomes.

Methods

A total of 38 patients with stage I ($n = 18$) or stage II ($n = 20$) KD were retrospectively enrolled. All underwent a modified procedure under local anesthesia: bilateral pedicle placement of headless cannulated screws, transmidline cement delivery using a steerable cannula (Ascend™), and staged injection (high-viscosity cement followed by low-viscosity cement). Clinical outcomes were assessed by visual analogue scale (VAS) and Oswestry Disability Index (ODI). Radiological outcomes included anterior vertebral height (AVH) and Cobb angle. Evaluations were performed preoperatively, at postoperative day 1, 6 months, 12 months, and at final follow-up (mean 17.2 months). Complications were recorded.

Results

Significant improvements were observed postoperatively and maintained throughout follow-up. VAS decreased from 6.89 ± 0.87 preoperatively to 1.26 ± 0.61 at final follow-up ($P < 0.001$). ODI improved from $69.58 \pm 9.24\%$ to $17.89 \pm 7.03\%$ ($P < 0.001$). AVH and Cobb angle were both significantly restored at day 1 and remained stable without progressive kyphosis or height loss. Cement extravasation occurred in 15.8% and adjacent vertebral fracture in 5.3%. Stage I patients received larger cement volume than stage II (6.83 ± 1.17 vs. 5.78 ± 1.12 mL, $P = 0.008$), but final outcomes did not differ between groups (all $P > 0.05$).

Conclusions

The modified PVP combining bilateral cannulated screws, steerable cement delivery, and staged injection is safe and feasible for stage I and II KD. It provides sustained pain relief, functional improvement, and durable vertebral height and kyphosis correction, potentially preventing cement loosening and vertebral re-collapse.

1. Introduction

Kummell's disease (KD), also known as delayed post-traumatic vertebral osteonecrosis or vertebral avascular necrosis, is a relatively rare but characteristic spinal disorder [1–3]. It was first described by the German physician Herman Kummell in 1891 [4]. Its core feature is that after a typically mild spinal injury, patients experience an asymptomatic or mildly symptomatic "latent period" (ranging from weeks to months), followed by progressively worsening low back pain, kyphotic deformity, and even neurological dysfunction [5–8].

The exact pathogenesis of KD remains not fully understood [9]. However, it is generally believed that a minor vertebral compression fracture damages the terminal arteries within the vertebral body, leading to interruption of local blood supply and subsequent ischemic necrosis. During the healing process, the necrotic bone tissue cannot be effectively reconstructed, resulting in fragile trabecular bone structure. Under continuous or repeated axial loading, this eventually leads to intravertebral collapse, cavitation and delayed vertebral height loss [3, 10–11].

The classification of KD is an important basis for its diagnosis and treatment selection. Currently, the most widely used classification system in clinical practice is the three-stage system proposed by Li et al. [12], based on imaging findings and pathological progression. Stage I: Vertebral height loss is less than 20%, with no significant spinal kyphosis. An obvious vacuum cleft sign (IVC) is visible within the vertebral body on X-ray or CT. Stage II: Vertebral height loss exceeds 20%, with posterior wall cortical disruption and dynamic instability. Low back pain continues to worsen, and a progressive spinal kyphotic deformity begins to appear. Stage III: Severe vertebral collapse occurs. The fractured fragment of the posterior vertebral wall retropulses into the spinal canal, resulting in spinal cord or nerve root compression.

In previous literature [2, 5, 13–14], percutaneous vertebroplasty (PVP) or percutaneous kyphoplasty (PKP) was recommended for the treatment of stage I, stage II, and even stage III KD without neurological symptoms, with patients achieving good early clinical outcomes. However, long-term follow-up studies have revealed significant differences in imaging and long-term prognosis between patients with KD and those with simple osteoporotic fractures [11, 15]. On imaging, the PMMA in patients with KD mainly concentrates within the IVC, forming a cement mass. It does not achieve effective interlocking with the vertebral trabecular bone. A boundary and micromotion exist between the cement mass and the surrounding sclerotic bone of the IVC. Under the continuous effect of the grinding phenomenon, this eventually leads to cement loosening, progressive vertebral collapse and kyphosis, and even the development of neurological symptoms [16–17].

To prevent cement loosening within the IVC, various modified surgical techniques for KD have been proposed by researchers [10–11, 15–19]. However, their long-term clinical outcomes still require validation. The purpose of this study is to introduce a unique minimally invasive surgical technique for treating KD and to verify the safety, feasibility, and preliminary effectiveness of this technique during mid-to-long-term follow-up.

2. Patients and Methods

2.1 study design

Consecutive patients who underwent modified percutaneous vertebroplasty (PVP) for KD at the Department of Spinal Surgery, Yantaishan Hospital between March 2023 and March 2025 were retrospectively enrolled in this study. The inclusion criteria were as follows: (1) consistent with the diagnostic criteria of KD: a history of minor trauma followed by progressive low back pain after an asymptomatic latent phase; (2) intravertebral vacuum cleft (IVC) confirmed on computed tomography (CT), with cleft regions presenting as hyperintense signals (fluid collection) or hypointense signals (gas formation) on magnetic resonance imaging (MRI); (3) single-segment vertebral involvement; (4) Li stage I or II disease; (5) bone mineral density (BMD) T-score ≤ -2.5 standard deviations (SD); (6) signed written informed consent available. Exclusion criteria included: (1) stage III KD; (2) multi-level vertebral fractures; (3) spinal infection, spinal tumor or spinal tuberculosis; (4) severe comorbid systemic diseases precluding surgical tolerance; (5) previous history of spinal surgery; (6) coagulation disorders or cognitive dysfunction.

2.2 Surgical Procedure

All surgical procedures were completed under local anesthesia by two senior surgeons from the minimally invasive spinal surgery team, each with clinical experience of more than 300 conventional PVP operations. Patients were placed in hyperextension prone position on the operating table, and a G-arm fluoroscopy system was positioned and adjusted to acquire standard anteroposterior and lateral intraoperative fluoroscopic images throughout the operation. Following local anesthesia, percutaneous puncture was performed under fluoroscopic guidance targeting the posterior margin of the IVC. A guidewire was placed in the same manner as conventional PVP after successful puncture, followed by removal of the trocar. Two sequentially sized customized muscular dilator cannulas with a maximum inner diameter of 5.5 mm were advanced over the guidewire, after which a headless cannulated screw (Double Medical Technology Inc., Xiamen, China; 5.2 mm $\times$ 40 mm)

was inserted along the guidewire and fully seated into the pedicle under fluoroscopic confirmation; the guidewire and dilator cannulas were subsequently retrieved once satisfactory screw position was verified. Contralateral pedicular puncture and guidewire placement were completed using an identical operative technique. An Ascend™ steerable bone cement delivery cannula (Langmed Medical, Shanghai, China) was advanced over the contralateral guidewire, and the distal curved tip of the Ascend™ cannula was adjusted to cross the midline of the vertebral body and rest adjacent to the previously implanted ipsilateral screw. High-viscosity polymethylmethacrylate (PMMA, Tecres, Spa.) bone cement was subsequently injected into the vertebral body via the Ascend™ system to primarily fill the contralateral IVC and the peri-screw space. The curved Ascend™ delivery cannula was gradually retracted within the IVC with repeated small-volume cement injections to achieve maximal obliteration of the cleft cavity. After straightening the Ascend™ cannula tip to a 0° angle, low-viscosity PMMA cement was infused into the residual IVC and surrounding vertebral bone through the same device. Upon fluoroscopic confirmation of adequate cement distribution, the entire Ascend™ bone cement injector kit was rapidly withdrawn. A guidewire was reintroduced along the same trajectory, and a second cannulated screw was implanted into the contralateral pedicle before cement polymerization to facilitate rigid anchorage between bone cement and the screw implant (Fig. 1A-H). Intraoperative real-time G-arm fluoroscopy was repeatedly applied during the entire procedure to minimize the risk of cement extravasation, while continuous vital sign monitoring was performed to guarantee perioperative patient safety.

2.3 Clinical and Radiological Assessment

Clinical and radiological evaluations were scheduled preoperatively, at postoperative day 1, 6 months, 12 months after surgery, and at the final follow-up visit. The visual analogue scale (VAS) was adopted to quantify low back pain severity, and the Oswestry Disability Index (ODI) was used to assess spinal functional impairment. All radiographic data were retrieved and measured via the hospital's authorized Picture Archiving and Communication System (PACS). Anterior vertebral body height (AVH) was measured on lateral plain radiographs or sagittal reformatted CT images. The Cobb angle was defined as the intersecting angle between two tangent lines drawn along the superior endplate of the vertebra above the fractured level and the inferior endplate of the vertebra below the fractured level, respectively. Raw clinical outcome data (VAS and ODI scores) were collected directly from standardized follow-up questionnaires completed by participants. All AVH and Cobb angle radiographic measurements were independently performed by two experienced attending spinal surgeons using the built-in standardized digital measurement tools embedded in the institutional PACS platform. Discrepancies exceeding 10% between the two examiners' measurements were resolved via joint re-evaluation and consensus discussion to ensure uniform assessment across all enrolled cases.

2.4 Anti-Osteoporotic Management

All patients were recommended to receive standardized anti-osteoporotic medication throughout the perioperative period and entire follow-up period. Routine daily oral calcium and vitamin D supplementation was prescribed for every participant. Additional anti-osteoporotic pharmacotherapy was individualized according to current clinical guidelines and each patient's clinical status. Oral bisphosphonates served as the first-line agent for patients with preserved renal function. Denosumab was selected as an alternative option for patients with impaired renal function or bisphosphonate intolerance. For patients with severe osteoporosis (BMD T-score ≤ -3.0 SD) without contraindications and affordable medical expense, teriparatide was prioritized as the first-line anabolic agent owing to its proven efficacy in improving bone mineral density and reducing subsequent fracture risk. The final selection of anti-osteoporotic regimens was based on individualized considerations including renal function, medication cost, patient preference and potential adverse drug reactions.

3. Statistical Analysis

All statistical analyses were conducted using SPSS version 22.0 software (IBM Corp., Armonk, NY, USA). Measurement data were expressed as mean $\pm$ standard deviation (Mean $\pm$ SD), while enumeration data were presented as case number and percentage (n/%). Intergroup comparisons of continuous variables were performed with independent-samples t-test, and categorical variables were compared using the Chi-square test or Fisher's exact test when the

theoretical frequency was less than 5. Repeated-measures analysis of variance (ANOVA) was utilized to compare longitudinal clinical and radiological outcomes across different follow-up time points; upon detection of statistically significant overall differences, post-hoc multiple comparisons with Bonferroni correction were implemented for pairwise comparisons between each postoperative time point and baseline preoperative values. All statistical tests were two-tailed, and a P value less than 0.05 was defined as statistically significant.

4. Results

4.1. Baseline Demographics and Perioperative Parameters

A total of 38 patients with KD were enrolled in the present study, including 18 patients with stage I and 20 patients with stage II disease. No significant intergroup differences were observed regarding gender distribution ($P = 0.986$), age ($P = 0.683$), bone mineral density T-score ($P = 0.512$), fractured vertebral level distribution ($P = 0.721$), intraoperative blood loss ($P = 0.654$), operative duration ($P = 0.327$), and final follow-up period ($P = 0.549$), confirming comparable baseline characteristics between the two groups (Table 1).

Notably, patients with stage I KD received a significantly larger volume of injected bone cement compared with stage II counterparts (6.83 ± 1.17 mL vs. 5.78 ± 1.12 mL, $P = 0.008$). The overall complication rate was 21.1% (8/38), consisting of 6 cases of cement extravasation (15.8%) and 2 cases of adjacent vertebral fracture (5.3%). No statistically significant differences were found between stage I and stage II groups in terms of cement leakage rate (11.1% vs. 20.0%, $P = 0.438$), adjacent vertebral fracture rate (0.0% vs. 10.0%, $P = 0.154$), or total complication incidence (11.1% vs. 30.0%, $P = 0.116$) (Table 1).

4.2. Serial Changes in Clinical and Radiological Outcomes for the Entire Cohort

Serial clinical and radiological indicators of all 38 patients were recorded preoperatively, at postoperative day 1, 6 months, 12 months postoperatively, and at the final follow-up (Table 2).

4.2.1 Clinical outcomes

VAS score decreased markedly from the preoperative value of 6.89 ± 0.87 to 2.74 ± 0.72 at postoperative day 1, further improved to 1.42 ± 0.55 at 6 months postoperatively, and remained stable thereafter with a final follow-up score of 1.26 ± 0.61 . Repeated-measures ANOVA revealed an overall significant difference across all time points ($F = 128.54$, $P < 0.001$). The ODI declined significantly from preoperative $69.58 \pm 9.24\%$ to $28.63 \pm 7.16\%$ on postoperative day 1, reached $19.47 \pm 6.82\%$ at 6 months, and was $17.89 \pm 7.03\%$ at the final follow-up, with significant overall inter-time-point differences ($F = 96.72$, $P < 0.001$). Post-hoc analysis demonstrated that both VAS and ODI scores at all postoperative time points were significantly superior to preoperative baseline values (all $P < 0.05$), whereas no significant differences existed among different postoperative time points (all $P > 0.05$).

4.2.2 Radiological outcomes

AVH changed from preoperative 11.63 ± 2.15 mm to 9.87 ± 1.86 mm at postoperative day 1, 10.02 ± 1.91 mm at 6 months, and 10.21 ± 1.97 mm at the final follow-up, with statistically significant overall temporal variation ($F = 42.36$, $P < 0.001$). The Cobb angle was significantly corrected from preoperative $11.87 \pm 3.42^\circ$ to $9.15 \pm 2.63^\circ$ at postoperative day 1, followed by $9.22 \pm 2.58^\circ$ at 6 months and $9.34 \pm 2.65^\circ$ at final follow-up ($F = 38.69$, $P < 0.001$). Post-hoc comparisons showed that AVH and Cobb angle at all postoperative time points were significantly improved relative to preoperative status (all $P < 0.05$), while no significant differences were detected among various postoperative visits (all $P > 0.05$). These findings indicated durable radiological correction without progressive kyphosis or recurrent vertebral height loss during mid-to-long-term follow-up (Fig 2).

4.3. Comparison of Final Follow-up Outcomes Between Stage I and Stage II Patients

At the final follow-up, there were no significant differences between stage I and stage II groups in VAS score (1.17 ± 0.58 vs. 1.34 ± 0.63 , $t = 0.89$, $P = 0.379$), ODI ($16.94 \pm 6.75\%$ vs. $18.75 \pm 7.26\%$, $t = 0.78$, $P = 0.441$), AVH (10.32 ± 1.89 mm vs. 10.11 ± 2.02 mm, $t = 0.34$, $P = 0.734$), and Cobb angle ($8.76 \pm 2.41^\circ$ vs. $9.83 \pm 2.79^\circ$, $t = 1.25$, $P = 0.219$) (Table 3). These results suggested that modified PVP yielded comparable mid-to-long-term clinical and radiological efficacy in patients with stage I and II KD (Fig 2).

5. Discussion

KD is defined as delayed post-traumatic osteonecrosis of the vertebral body, whose core pathological features consist of intravertebral vacuum cleft formation and progressive vertebral collapse secondary to ischemic osteonecrosis [1–3, 15, 19–21]. Similar to the treatment for ordinary osteoporotic vertebral compression fracture (OVCF), PVP or PKP remains the preferred surgical option for patients with stage I and II KD [5, 13]. However, the presence of IVC leads to distinct cement-bone interaction between KD and conventional OVCF. In routine OVCF, bone cement fully interdigitates with intravertebral trabeculae, whereas cement tends to accumulate predominantly within the IVC cavity in KD, forming a clear demarcation from surrounding vertebral bone without sufficient mechanical interlock. Micro-motion and abrasive wear occurring at the interface between cement and sclerotic bone eventually trigger recurrent vertebral collapse, progressive kyphosis, and even neurological deficits resulting from spinal cord compression [10]. As reported by Heo et al. [22], recurrent vertebral collapse developed in 6 out of 21 KD patients treated with conventional PVP, corresponding to a re-collapse rate of 28.57%.

Given that cement loosening and subsequent vertebral collapse are major determinants of poor long-term postoperative outcomes, multiple modified surgical techniques have been proposed by researchers to tackle these drawbacks [5, 23–26]. As reported by Dai et al. [23], 41 patients underwent PVP combined with bilateral pedicular cement anchoring and received mid-to-long-term follow-up. The relevant outcomes confirmed that this technique significantly enhances cement stability and prevents intravertebral cement loosening and migration. Nevertheless, attention should be paid to its inherent

drawback: the procedure elevates the potential risk of peripedicular cement extravasation during operation. Zhong et al.[27] treated 50 KD patients with hollow bridging screws combined with kyphoplasty and concluded the technique was safe and effective, featuring improved biomechanical performance and reduced cement loosening compared with conventional PKP or PKP combined with pediculoplasty. Related finite element analyses further confirmed the mechanical stability of bridging screws for KD treatment [28–29]. However, under the standard operative protocol for KD, bone cement is injected into the IVC prior to bridging screw placement. Due to the rapid setting of intravertebral cement, inadequate integration between screws and solidified cement is prone to occur, particularly for screws implanted at the final stage.

Distinct from previous techniques, the core technical advantages of the this modified procedure applied in the current study include three key aspects: (1) Bilateral implantation of headless cannulated screws to establish immediate internal vertebral support and mechanical anchor points; (2) Application of the Ascend™ steerable bone cement delivery cannula, which enables transmidline cement injection for precise filling of the contralateral IVC and periscrew space, thereby constructing an integrated locking complex consisting of bone cement, pedicle screw and host vertebral bone; (3) A staged cement injection protocol: high-viscosity PMMA cement is injected initially to obliterate the IVC and the space surrounding contralateral screws, followed by low-viscosity cement infusion for residual void filling to improve osseointegration at the cement-vertebra interface. This tailored design effectively eliminates the common pitfall of isolated cement block confined inside IVC without trabecular interlock after conventional PVP. Benefiting from screw-mediated interfacial anchorage and three-dimensional cement distribution, the construct is theoretically capable of resisting persistent axial loading and interfacial abrasion, minimizing the risks of cement loosening, recurrent vertebral collapse and progressive kyphotic deformity.

A total of 38 patients with stage I or II KD were enrolled in this cohort with a median follow-up of 17.16 months. Significant and sustained improvements in both clinical and radiographic parameters were achieved after the modified surgery. Clinically, the VAS score decreased significantly from a preoperative baseline of 6.89 ± 0.87 to 2.74 ± 0.72 at postoperative day 1 and was maintained at 1.26 ± 0.61 at the final follow-up ($P < 0.001$). The ODI also improved markedly from $69.58 \pm 9.24\%$ preoperatively to $17.89 \pm 7.03\%$ at the last follow-up ($P < 0.001$). Radiographically, significant restoration of AVH and correction of Cobb angle were accomplished at postoperative day 1 without obvious height loss or progressive kyphosis during mid-to-long-term follow-up, confirming favorable biomechanical stability of the proposed surgical technique.

Although significantly larger cement volume was injected in stage I patients relative to stage II counterparts (6.83 ± 1.17 mL vs. 5.78 ± 1.12 mL, $P = 0.008$), no intergroup differences were detected in VAS, ODI, AVH or Cobb angle at final follow-up (all $P > 0.05$), indicating comparable therapeutic efficacy of this modified procedure across the two disease stages. The intact anatomical space of IVC in stage I lesions allows larger-volume cement filling; in contrast, stage II KD is characterized by disrupted posterior vertebral cortex and progressive spinal instability, which necessitates more cautious intraoperative manipulation and consequently restricts cement injection volume. Nonetheless, such cement volume discrepancy does not compromise final clinical efficacy, demonstrating reliable adaptability and safety of the present technique for stage II KD as well.

6. Limitations of the Study

This study has several limitations. First, the sample size was small ($n = 38$), and it was a single-center, non-randomized controlled trial, which may lead to selection bias. Second, although the follow-up period reached a medium-to-long term of 17 months, it was still insufficient to evaluate the long-term stability of the bone cement-screw interface and adjacent segment degeneration over an extended period (e.g., more than 5 years). Third, traditional percutaneous vertebroplasty (PVP) or percutaneous kyphoplasty (PKP) was not set as the control group, so the relative advantages of the modified surgical procedure could not be directly compared. Further multicenter, large-sample and randomized controlled studies with prolonged follow-up are required to verify the clinical value of this surgical technique.

7. Conclusions

The modified minimally invasive technique combining bilateral cannulated screws, steerable cement delivery, and staged injection can achieve favorable safety, feasibility and preliminary clinical efficacy in the treatment of stage I and II KD. This technique can effectively alleviate pain, improve spinal function, and sustain vertebral height and kyphosis correction during medium-to-long-term follow-up. Moreover, it also offers a promising solution to cement loosening and vertebral re-collapse, common complications following conventional PVP or PKP.

Abbreviation

KD	Kümmell's disease
PVP	percutaneous vertebroplasty
PKP	percutaneous kyphoplasty
IVC	intravertebral vacuum cleft
OVCF	osteoporotic vertebral compression fracture
CT	computed tomography
MRI	magnetic resonance imaging
PMMA	polymethylmethacrylate

VAS visual analogue scale

ODI Oswestry disability index

AVH anterior vertebral height

BMD bone mineral density

DXA dual energy X-ray absorptiometry

Declarations

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author Contributions Statement

Huimin Wang designed the research plan and wrote the manuscript. Xiaofeng Li performed the statistical analysis of the research data and assisted Jianmin Wang in the writing of the manuscript. Wei Du, Xurisun and Haiqing Tian were responsible for data collection, image preparation and Software processing. Dexin Zou was responsible for supervision, funding acquisition, and final manuscript approval. All authors read and approved the final version of the manuscript.

Consent to participate

Written informed consent was obtained from each patient and this study was approved by Ethics Committee of Yantaishan Hospital (no.2025028). The author declares that the methods carried out in this study were in accordance with the Declaration of Helsinki.

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Conflict of interest

The authors declare that they have no conflict of financial and non-financial interest.

Consent for publication

All the authors agree to the publication of the article.

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Tables

Talbe 1. Baseline Characteristics and Perioperative Data of Patients

Variables	All Patients (n=38)	StageⅡ (n=18)	StageⅢ (n=20)
Sex (M/F)	20/18	10/8	10/10
Age (y)	74.95 ± 4.79	75.33 ± 4.92	74.60 ± 4.73
BMD (T-score)	-3.49 ± 0.61	-3.42 ± 0.58	-3.55 ± 0.64
Level (n, %)			
T7-T9	4 (10.5%)	2 (11.1%)	2 (10.0%)
T10-T12	20 (52.6%)	10 (55.6%)	10 (50.0%)
L1-L3	14 (36.8%)	6 (33.3%)	8 (40.0%)
IVC (ml)	6.26 ± 1.24	6.83 ± 1.17	5.78 ± 1.12
BL (ml)	12.34 ± 2.76	12.56 ± 2.91	12.15 ± 2.68
OT (min)	28.63 ± 4.51	27.89 ± 4.23	29.25 ± 4.72
FFU (mon)	17.16 ± 2.15	17.39 ± 2.31	16.95 ± 2.02
Complications (n, %)			
BCL	6 (15.8%)	2 (11.1%)	4 (20.0%)
AVF	2 (5.3%)	0 (0.0%)	2 (10.0%)
Total complications	8 (21.1%)	2 (11.1%)	6 (30.0%)

M: male; F: female; y: year; BMD: bone mineral density; IVC: injected cement volume; ml: milliliter; BL: blood loss; OT: operation time; BCL: bone cement leakage; AVF: anterior vertebral fracture

Table 2. Clinical and Radiographic Outcomes at Different Time Points (n=38)

Variables	Pre-OP	POD1	PO6m	PO1y	FFU	F value	P value
VAS score	6.89±0.87	2.74±0.72	1.42±0.55	1.37±0.59	1.26±0.61	128.54 [§]	<0.001
ODI score (%)	69.58±9.24	28.63±7.16	19.47±6.82	18.92±6.94	17.89±7.03	96.72 [§]	<0.001
AVH (mm)	11.63±2.15	9.87±1.86	10.02±1.91	10.15±1.94	10.21±1.97	42.36 [§]	<0.001
Cobb angle (°)	11.87±3.42	9.15±2.63	9.22±2.58	9.28±2.61	9.34±2.65	38.69 [§]	<0.001

[§] P<0.05 vs. Pre-OP; No significant progression among postoperative time points, P>0.05[§]Pre-OP: pre-operation; POD1: post-operative day 1; PO6m: post-operative 6 months; PO1y: post-operative 1 year; FFU: final follow-up; mon: month; VAS: visual Analogue Scale; ODI: Oswestry Disability Index; AVH: anterior vertebral height.

Table 3. Outcomes at Final Follow-Up Between Stage Ⅱ and Stage Ⅲ Groups

Variables	Stage Ⅱ (n=18)	Stage Ⅲ (n=20)	t -value	P value
VAS score (FFU)	1.17±0.58	1.34±0.63	0.89	0.379
ODI score (FFU, %)	16.94±6.75	18.75±7.26	0.78	0.441
AVH (FFU, mm)	10.32±1.89	10.11±2.02	0.34	0.734
Cobb angle (FFU, °)	8.76±2.41	9.83±2.79	1.25	0.219

VAS: visual Analogue Scale; ODI: Oswestry Disability Index; AVH: anterior vertebral height.

Figures

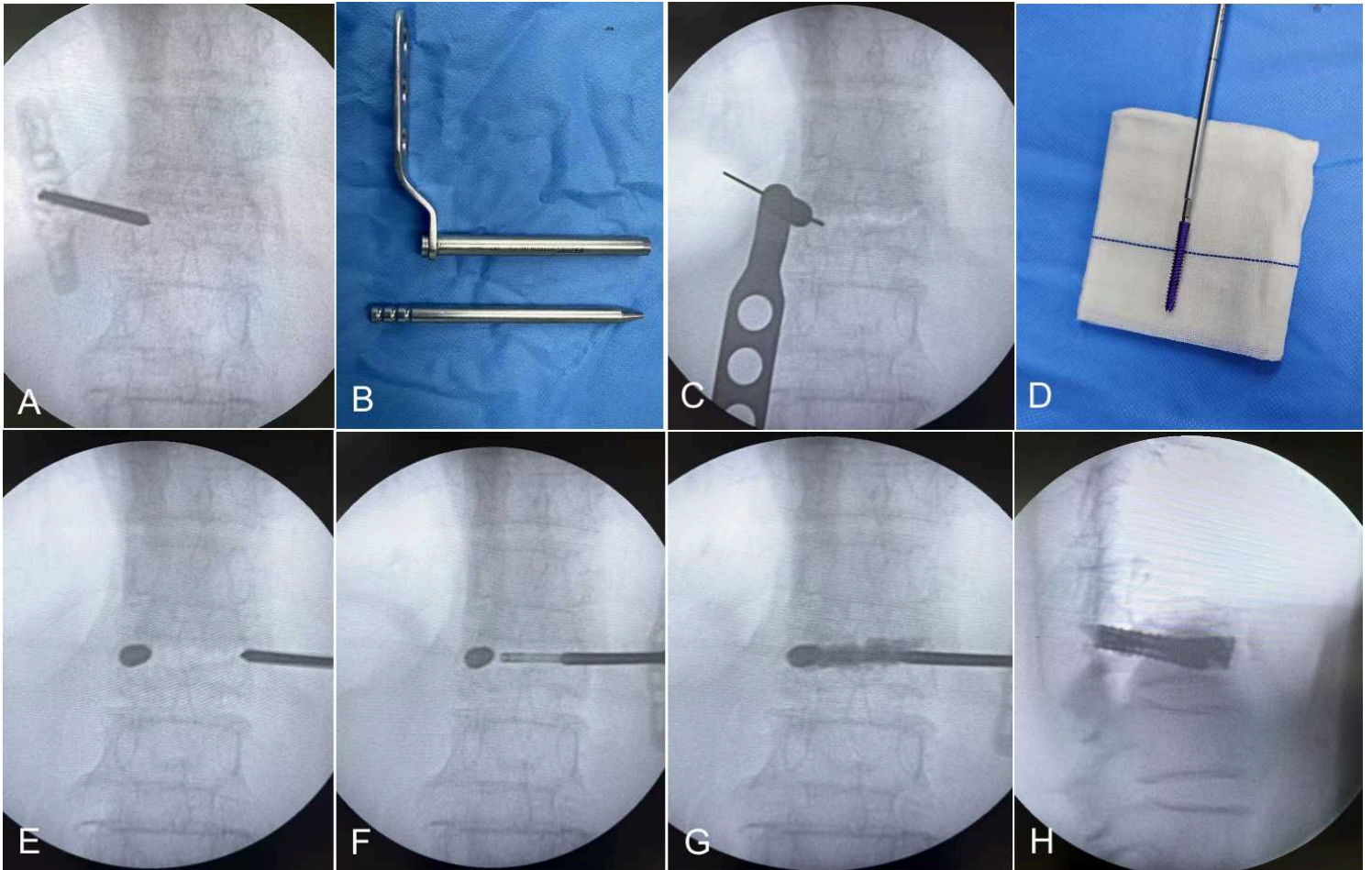


Figure 1

Illustration of the modified surgical technique for KD. Percutaneous puncture was performed as conventional PVP (A) . Two customized muscular dilator cannulas were advanced over the guidewire, a headless cannulated screw was inserted into the pedicle (B-E); High-viscosity PMMA cement was injected via the steerable cannula to obliterate the IVC across the vertebral midline (F). Low-viscosity PMMA cement was infused for secondary filling (G). The contralateral cannulated screw was placed before cement polymerization to form an integrated screw-cement-vertebra complex (H).

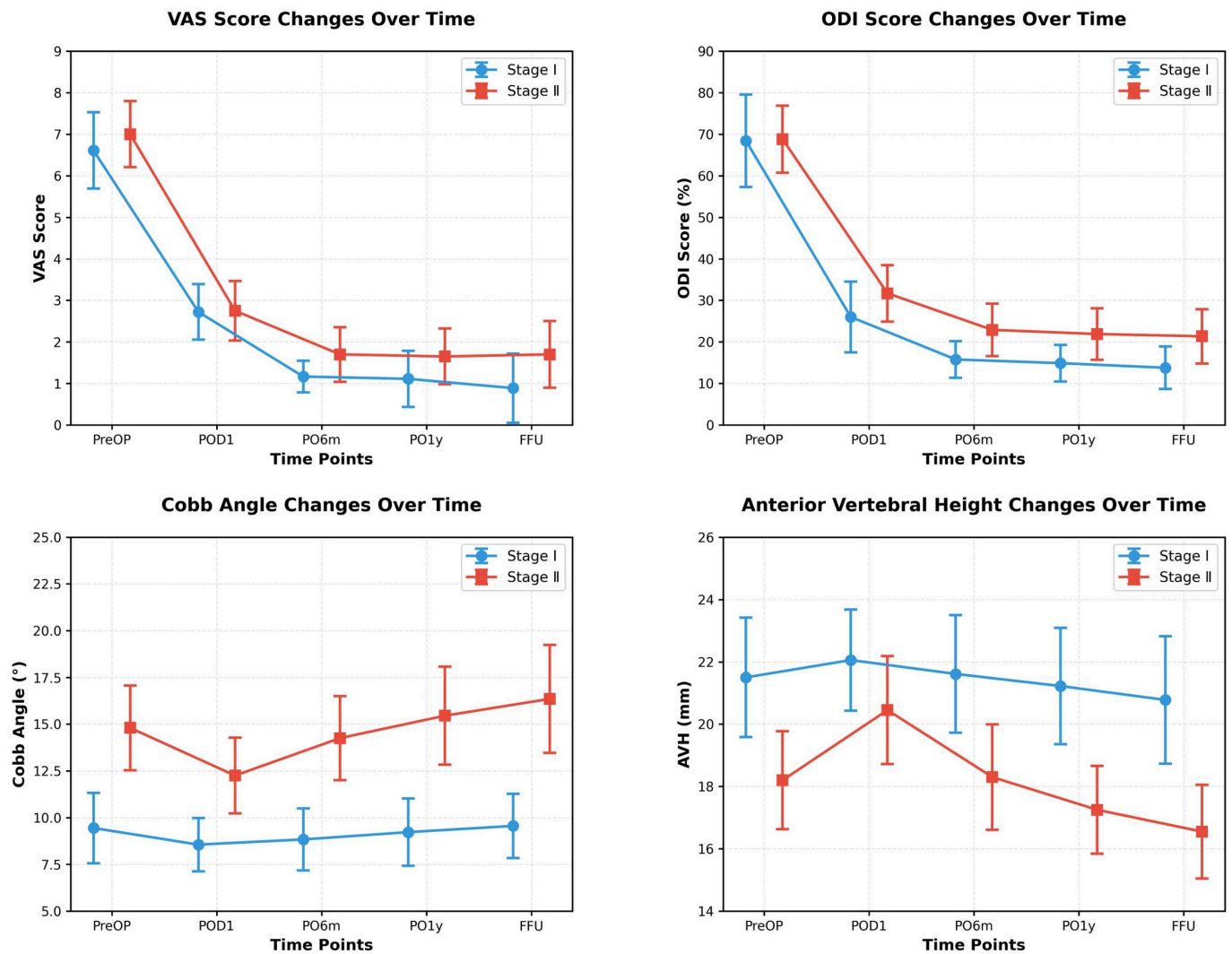


Figure 2

Serial changes of clinical and radiographic outcome metrics in Stage I and Stage II patients. Four subplots illustrate the longitudinal trends of VAS pain score, Oswestry Disability Index (ODI), Cobb angle, and anterior vertebral height (AVH) across all time points. Blue lines represent Stage I patients, red lines represent Stage II patients; error bars indicate the corresponding variability of each measurement. Time points: PreOP = pre-operation, POD1 = postoperative day 1, PO6m = postoperative 6 months, PO1y = postoperative 1 year, FFU = final follow-up.