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RESEARCH

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The correction range of lumbosacral curve vertebral body tilt in degenerative scoliosis for achieving postoperative coronal balance

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Abstract

Purpose To explore the relationship between lumbosacral curve vertebral body tilt correction and postoperative coronal balance in adult degenerative scoliosis to determine the ideal target values for the tilt correction.

Methods We conducted a retrospective analysis of 144 patients who underwent surgery between January 2017 and December 2023. Patients were classified based on the preoperative Obeid classification and fixation segment length into Concave Long Segment (Concave-L, $n=41$), Concave Short Segment (Concave-S, $n=33$), Convex Long Segment (Convex-L, $n=39$), and Convex Short Segment (Convex-S, $n=31$). Changes in coronal and sagittal radiographic parameters and the correlation between the correction percentage of the most tilted vertebra (L4 or L5) and postoperative coronal balance distance (CBD) were assessed.

Results Significant postoperative improvements in CBD, maximum coronal tilt, and Cobb angle were observed in the Concave-L, Convex-L, and Convex-S groups. The Concave-S group exhibited significant changes only in Cobb angle and maximum coronal tilt, but not CBD. A significant negative correlation existed between postoperative CBD and the correction ratio of maximum coronal tilt in the convex malalignment (r=-0.629, $P<0.001$), with the regression equation: Postoperative CBD = 32.99 - (28.82 × Correction Ratio of Coronal Tilt). A correction ratio exceeding 45% at L4 or L5 tilt predicted a postoperative CBD within 20 mm.

Conclusion Both short and long segment fusions effectively correct convex coronal malalignment, but concave malalignment requires long segment fusion for adequate correction. Optimal coronal balance in convex malalignment is achieved when the maximum tilt correction ratio exceeds 45%.

Keywords Coronal balance distance, Fractional curve, Coronal Tilt, Degenerative scoliosis

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Introduction

Adult degenerative scoliosis (ADS) is marked by an onset of primary spinal curvature after reaching skeletal maturity, accompanied by degenerative changes and no prior scoliosis history [1]. Common symptoms among ADS patients include lumbar and thoracic pain, radicular symptoms, and intermittent claudication, often with coronal or sagittal plane imbalance [2]. In ADS, compensatory curves below the main lumbosacral curve are termed fractional curves [3]. Radicular pain on the concave side of the lumbosacral curve (involving L4, L5, and S1 nerve roots) represents the most common cause of radicular symptoms in ADS patients [4]. Current surgical interventions include decompression, short-segment fixation and fusion, or long-segment fixation and fusion [5]. ADS predominantly affects middle-aged and elderly individuals who may have multiple comorbidities, necessitating a careful balance between surgical tolerance and efficacy. Therefore, the choice between long-segment and short-segment fusion is still debated.

In the treatment-oriented guideline proposed by Obeid et al. [6], coronal malalignment is classified into two types: Concave (Type 1) and Convex (Type 2). Concave (Obeid Type 1) is defined as coronal malalignment where the coronal T1 plumbline falls on the concave side of the main coronal curve. Convex (Obeid Type 2) refers to coronal malalignment where the coronal T1 plumbline falls on the convex side of the main coronal curve. In convex malalignment cases with small thoracolumbar curve and large lumbosacral curve, the surgical correction should be focus on the lumbosacral curve. However, due to the greater difficulty in correcting the lumbosacral curve compared to the thoracolumbar curve, suboptimal postoperative balance correction or even worsening imbalance is often unavoidable [7]. Precisely planning the corrective strategy is crucial for reducing the risk of postoperative coronal decompensation due to insufficient correction of the lumbosacral curve. The degree of the lumbosacral vertebra tilt is important indicator for assessing coronal alignment intraoperatively. Surgeons need to know the target values for the degree of vertebral tilt or the correction percentage, which has been lacking in previous research.

This retrospective study evaluates the Obeid coronal imbalance classification and examines preoperative and postoperative imaging in ADS patients to explore the relationship between lumbosacral curve vertebral body tilt correction and postoperative coronal balance to determine the ideal target values.

Materials and methods

Study design

Inclusion Criteria: Patients with adult degenerative scoliosis (Cobb angle > 10°), experiencing preoperative lumbar back pain and radicular pain in the lower limbs, and a coronal balance distance (CBD) > 20 mm (the distance between the vertical line from T1 to the midline of the sacrum), who display curves in the lumbosacral region, were included. All participants underwent posterior column osteotomies (PCOs), with fixation spanning at least two vertebrae from L4 to S1.

Exclusion Criteria: Patients were excluded if they had a CBD ≤ 20 mm, concurrent infection or tumor, osteoporosis, hemiplegia, moderate to severe renal or hepatic disease, diabetes with chronic complications, incomplete imaging data, or a history of lumbar spine surgery. Patients undergoing pelvic fixation (including the use of iliac screws or S2AI screws) or those who underwent three-column osteotomies (3CO) or other extensive osteotomies more than grade III were not included in this study.

Following these criteria, a retrospective analysis was conducted on patients who received the surgery between January 2017 and December 2023. The study conformed to the Declaration of Helsinki and was approved by the Ethics Committee of Tianjin Union Medical Center (Medical Ethical Review No. 2024B104), with informed consent obtained from all participants.

Patients were classified based on the Obeid classification [6] into concave and convex types, depending on the side of the main curve where the vertical line from T1 fell. They were further categorized into short-segment (1 ≤ fusion segments < 3, including at least two vertebral bodies from the lumbosacral region) and long-segment groups (fusion segments ≥ 3, including at least two vertebral bodies from the lumbosacral region).

Radiological evaluation

Radiographic measurements were performed by two senior spine surgery residents. The reliability of the measurements was first tested in a sample of 30 patients. Radiographic data were randomly assigned to the two raters with a two-week interval between measurements. Intra- and inter-observer reliability was assessed using the intraclass correlation coefficient (ICC).

Preoperative and three-day postoperative full-spine anteroposterior and lateral X-rays were conducted to assess coronal and sagittal plane balance. The following parameters were measured to assess coronal and sagittal plane balance:

- Coronal balance distance (CBD): the distance between the plumb line from the sacrum and the plumb line from T1.
- Coronal tilt: the angle between the upper endplate of L4 or L5 vertebra and the horizontal line.

- Cobb angle: the angle between the upper endplate of the superior vertebra and the lower endplate of the inferior vertebra in the scoliotic curve.
- Pelvic incidence (PI): the angle between the line connecting the midpoint of the sacral endplate and the midpoint of the bilateral femoral heads and the vertical line passing through the midpoint of the sacral endplate.
- Sacral slope (SS): the angle between the sacral plateau and the horizontal line.
- Lumbar lordosis (LL): the angle between the upper endplate of L1 and the upper endplate of S1.
- Pelvic tilt (PT): the angle between the line connecting the midpoint of the sacral axis and the midpoint of the sacral plateau and the plumb line.
- Thoracic kyphosis (TK): the angle formed between the upper endplate of T5 and the lower endplate of T12.
- Sagittal vertical axis (SVA): the distance between the plumb line from C7 and the posterior edge of S1.

We selected the vertebra with the larger preoperative coronal tilt angle at L4 or L5 level and calculated the maximum coronal tilt correction ratio to evaluate the degree of lumbosacral curve correction. The calculation method was as follows:

$$Correction\ Ratio\ of\ Coronal\ Tilt = \frac{Preop\ Tilt\ Angle\ -\ Postop\ Tilt\ Angle}{Preop\ Tilt\ Angle} \times 100\%$$

All radiological measurements in this study were performed by two spinal physicians, and the mean values were taken.

Surgical technique

Surgical procedures were performed under general anesthesia with patients in the prone position. Standard sterilization and draping were followed by a midline posterior approach, sequential incisions through skin, subcutaneous tissue, and lumbar fascia, and meticulous hemostasis using electrocautery. The laminae and facet joints on both sides were exposed, and pedicle screws were inserted. Correction of the deformity was achieved using posterior column osteotomy. Interbody fusion cages were placed on the convex side of the scoliosis. Pre-bent rods of appropriate curvature and length were engaged into the pedicle screws. Distraction was applied on the concave side and compression on the convex side to achieve vertebral body leveling of the lumbosacral region. Intraoperative fluoroscopy was utilized to confirm and evaluate the alignment. Subsequently, all screw caps were tightened. After bone grafting, the wound was irrigated, a drainage tube was placed, and the incision was closed layer by layer.

Statistical analysis

Statistical Analysis: Data analysis employed SPSS 25.0, using variance analysis, chi-square, t-tests, and rank sum tests for preoperative and postoperative comparisons, considering a p-value < 0.05 as statistically significant. Pearson correlation analysis and linear regression were used to explore the relationship between the lumbosacral curve's maximum coronal tilt correction ratio and postoperative CBD in both convex and concave cases. All normally distributed variables were presented as mean ± standard deviation (SD) for descriptive statistics. Non-parametric data (e.g., the number of fused levels in surgery) were described using the median and interquartile range (IQR).

Results

Patient demographic data

This study included 144 patients diagnosed with ADS who underwent posterior spinal fusion surgery. The distribution of cases was as follows: 41 Concave-L (long fusion segments), 33 Concave-S (short fusion segments), 39 Convex-L (long fusion segments), and 31 Convex-S (short fusion segments). Patient characteristics are summarized in Table 1. The Shapiro-Wilk test confirmed normal distribution of age and BMI for each group. Levene's test indicated homogeneity of variance across these variables. The one-way ANOVA showed no significant differences in age ($P = 0.370$) or BMI ($P = 0.608$) across the groups. The chi-square test found no significant gender differences across groups ($P = 0.897$). The Kruskal-Wallis

Table 1 Patient demographic data

	Total *n* = 144	Concave-L *n* = 41	Concave-S *n* = 33	Convex-L *n* = 39	Convex-S *n* = 31	*P* value
Age (y)	62.58 ± 8.14	64.17 ± 7.34	62.79 ± 8.77	62.15 ± 8.24	60.81 ± 8.32	0.370
Gender M/F	47/97	12/29	12/21	12/27	11/20	0.897
BMI (kg/m^2)	25.79 ± 3.61	25.87 ± 3.68	25.26 ± 4.07	26.36 ± 2.91	25.55 ± 3.86	0.608
Number of fused levels	3 (2–4)	5 (4–5)	2 (2–2)	4 (4–5)	2 (1–2)	<.001[1] 0.214[2] 0.494[3]

BMI indicates Body Mass Index. The number of fused levels in surgery was a non-normally distributed variable and was described using the median (IQR). [1]The *P*-value represents the comparison among the four groups; [2]The *P*-value represents the comparison between the long-segment groups (Concave-L vs. Convex-L). [3]The *P*-value represents the comparison between the short-segment groups (Concave-S vs. Convex-S) test comparing the number of fused levels indicated a statistically significant difference among the four groups. However, pairwise comparisons within the long-segment group (Concave-L vs. Convex-L, $P=0.214$) and the short-segment group (Concave-S vs. Convex-S, $P=0.494$) showed no statistically significant differences, indicating consistent baseline data.

Analysis of coronal plane radiological parameters

In this study, the ICC values for radiographic measurement parameters ranged from a minimum of 0.804 to a maximum of 0.986 (ICC values: 0.9–1.0, excellent; 0.7–0.89, good; 0.5–0.69, fair; 0.25–0.49, poor; 0–0.24, low), indicating high measurement consistency (Table S1).

In the Concave-L group, the radiological coronal plane parameters (Table 2) showed that the coronal balance distance (CBD) decreased from 42.94 ± 18.57 mm preoperatively to 15.9 ± 12.06 mm postoperatively; the maximum coronal tilt (at L4 or L5) was reduced from 10.17 ± 5.08° preoperatively to 4.39 ± 3.83° postoperatively; and the Cobb angle improved from 23.05 ± 8.57° preoperatively to 8.61 ± 5.91° postoperatively, with all differences proving statistically significant ($P<0.001$).

In the Concave-S group, the radiological coronal plane parameters (Table 2) indicated that the maximum coronal tilt (at L4 or L5) was reduced from 7.64 ± 2.69° preoperatively to 4.39 ± 2.01° postoperatively; the Cobb angle improved from 15.09 ± 3.79° preoperatively to 7.67 ± 4.63° postoperatively, with both differences proving statistically significant ($P<0.001$). However, the coronal balance distance (CBD) increased from 31.21 ± 11.82 mm preoperatively to 26.6 ± 6.03 mm postoperatively, but this difference was not statistically significant ($P=0.078$).

Table 2 Comparison of preoperative and postoperative radiographic coronal parameters

	Pre-op	Post-op	*P* value
Concave-L group			
CBD (mm)	42.94 ± 18.57	15.9 ± 12.06	< 0.001
Max Coronal Tilt, L4 or L5 (°)	10.17 ± 5.08	4.39 ± 3.83	< 0.001
Cobb Angel (°)	23.05 ± 8.57	8.61 ± 5.91	< 0.001
Concave-S group			
CBD (mm)	31.21 ± 11.82	26.6 ± 6.03	0.078
Max Coronal Tilt, L4 or L5 (°)	7.64 ± 2.69	4.39 ± 2.01	< 0.001
Cobb Angel (°)	15.09 ± 3.79	7.67 ± 4.63	< 0.001
Convex-L group			
CBD (mm)	35.56 ± 11.81	23.14 ± 11.32	< 0.001
Max Coronal Tilt, L4 or L5 (°)	15 ± 8.14	8.72 ± 5	< 0.001
Cobb Angel (°)	19.28 ± 7.27	8.54 ± 8.52	< 0.001
Convex-S group			
CBD (mm)	30.34 ± 11.45	14.44 ± 11	< 0.001
Max Coronal Tilt, L4 or L5 (°)	6.23 ± 2.26	2.58 ± 1.88	< 0.001
Cobb Angel (°)	11.65 ± 6.07	3.65 ± 3.04	< 0.001

CBD indicates coronal balance distance

In the Convex-L group, the radiological coronal plane parameters (Table 2) indicated that the coronal balance distance (CBD) decreased from 35.56 ± 11.81 mm preoperatively to 23.14 ± 11.32 mm postoperatively ($P=0.007$); the maximum coronal tilt (at L4 or L5) was reduced from 15 ± 8.14° preoperatively to 8.72 ± 5° postoperatively ($P<0.001$); and the Cobb angle improved from 19.28 ± 7.27° preoperatively to 8.54 ± 8.52° postoperatively ($P<0.001$), with all differences being statistically significant.

In the Convex-S group, the radiological coronal plane parameters (Table 2) revealed that the coronal balance distance (CBD) decreased from 30.34 ± 11.45 mm preoperatively to 14.44 ± 11 mm postoperatively; the maximum coronal tilt (at L4 or L5) was reduced from 6.23 ± 2.26° preoperatively to 2.58 ± 1.88° postoperatively; and the Cobb angle improved from 11.65 ± 6.07° preoperatively to 3.65 ± 3.04° postoperatively, with all differences proving statistically significant ($P<0.001$).

Analysis of sagittal plane radiological parameters

Sagittal radiographic parameters also showed significant improvements postoperatively. Significant changes in parameters such as sacral slope (SS), lumbar lordosis (LL), pelvic tilt (PT), thoracic kyphosis (TK), and sagittal vertical axis (SVA) were noted across the groups, with each parameter's specific changes listed in Table 3.

Pearson correlation analysis and linear regression in the convex and concave groups

No significant correlation was found between postoperative CBD and the maximum coronal tilt correction ratio in the concave group ($P=0.715$, Fig. 1a). However, a significant negative correlation existed in the convex group ($r=-0.629$, $P<0.001$), indicating that greater correction of the maximum coronal tilt at L4/L5 was associated with smaller postoperative CBD, as depicted in Fig. 1b. In a linear regression analysis using postoperative CBD as the dependent variable and the maximum coronal tilt correction ratio as the independent variable, the resulting regression equation was:

$$Postoperative\,CBD = \\ 32.99 - 28.82 \times Coronary\,Tilt\,Correction\,Ratio$$

By substituting the maximum coronal tilt correction ratio into the regression equation, the predicted postoperative CBD value was determined, indicating that a postoperative CBD of 20 mm corresponds to a coronal tilt correction ratio of 45%.

Surgical parameters and patient-reported outcomes

The operative time and blood loss for each group are presented in Table 4. In both the concave and convex groups,

Table 3 Comparison of preoperative and postoperative radiographic sagittal parameters

	Pre-op	Post-op	*P* value
Concave-L group			
PI (°)	48.88 ± 8.78	47.61 ± 8.84	0.241
SS (°)	23.44 ± 8.41	26.32 ± 8.21	0.005
LL (°)	22.22 ± 11.67	31.24 ± 13.33	< 0.001
PT (°)	24.54 ± 10.45	19.83 ± 10.69	< 0.001
TK (°)	18.29 ± 9.84	21.73 ± 9.99	0.002
SVA (mm)	70.52 ± 44.84	40.48 ± 23.45	< 0.001
Concave-S group			
PI (°)	52.36 ± 7.96	49.88 ± 10.24	0.061
SS (°)	26.88 ± 7.34	27.58 ± 7.64	0.514
LL (°)	28.21 ± 11.33	36.18 ± 12.56	< 0.001
PT (°)	24.27 ± 7.73	19.12 ± 6.53	< 0.001
TK (°)	21.36 ± 9.18	22.55 ± 5.92	0.445
SVA (mm)	64.44 ± 37.23	33.71 ± 30.31	< 0.001
Convex-L group			
PI (°)	48.54 ± 9.46	48.59 ± 8.33	0.961
SS (°)	21.28 ± 8.43	20.9 ± 7.88	0.754
LL (°)	17.51 ± 13.67	26.79 ± 13.57	< 0.001
PT (°)	26.15 ± 7.79	23.82 ± 7.22	0.051
TK (°)	18.03 ± 12.01	19.69 ± 7.59	0.268
SVA (mm)	76.08 ± 26.98	62.73 ± 35.2	0.036
Convex-S group			
PI (°)	48.42 ± 9.1	46.68 ± 9.5	0.073
SS (°)	26.74 ± 7.51	28.77 ± 7.44	0.091
LL (°)	30.81 ± 17.24	37.1 ± 14.23	0.007
PT (°)	20.23 ± 8.69	19.23 ± 8.44	0.308
TK (°)	28 ± 18.45	27.48 ± 16.29	0.631
SVA (mm)	60.23 ± 42.3	40.29 ± 32.33	0.008

PI indicates pelvic incidence; SS, sacral slope; LL, lumbar lordosis; PT, pelvic tilt; TK, thoracic kyphosis; SVA, sagittal vertical axis

patients undergoing short-segment fusion surgery had shorter operative times and less blood loss compared to those undergoing long-segment fusion surgery. When comparing surgical parameters between the concave and convex groups within both long-segment and short-segment fusion, no significant differences were observed in operative time or blood loss.

We have complete preoperative and postoperative VAS pain score for the included cases, as presented in Table 5. These results demonstrate significant symptom improvement across all four groups, with no significant differences observed between the groups.

Discussion

Degenerative changes in the spine, such as intervertebral disc degeneration, vertebral osteoporosis, facet joint degeneration, and muscle atrophy, are primary factors causing coronal plane imbalance in ADS patients [8]. These factors lead to spinal instability and, subsequently, coronal plane imbalance. The CBD serves as the key indicator for assessing spinal coronal balance in ADS, with critical values identified at 2 cm [6, 9], 3 cm [10–12], and 4 cm [13, 14]. This study defines a significant coronal plane imbalance as a CBD exceeding 2 cm, in line with the Obeid classification [6] and the thresholds set by the International Spinal Deformity Study Group. Research on Patient-Reported Outcome Measures (PROMs) indicates that a CBD greater than 2 cm markedly affects patient functionality [15].

The Obeid classification [6] and Qiu classification [7] essentially describes different surgical strategies corresponding to varying primary curves in scoliosis, emphasizing the importance of correcting the primary lumbosacral curve and achieving horizontalization of the lumbosacral vertebrae in convex-type cases (Obeid

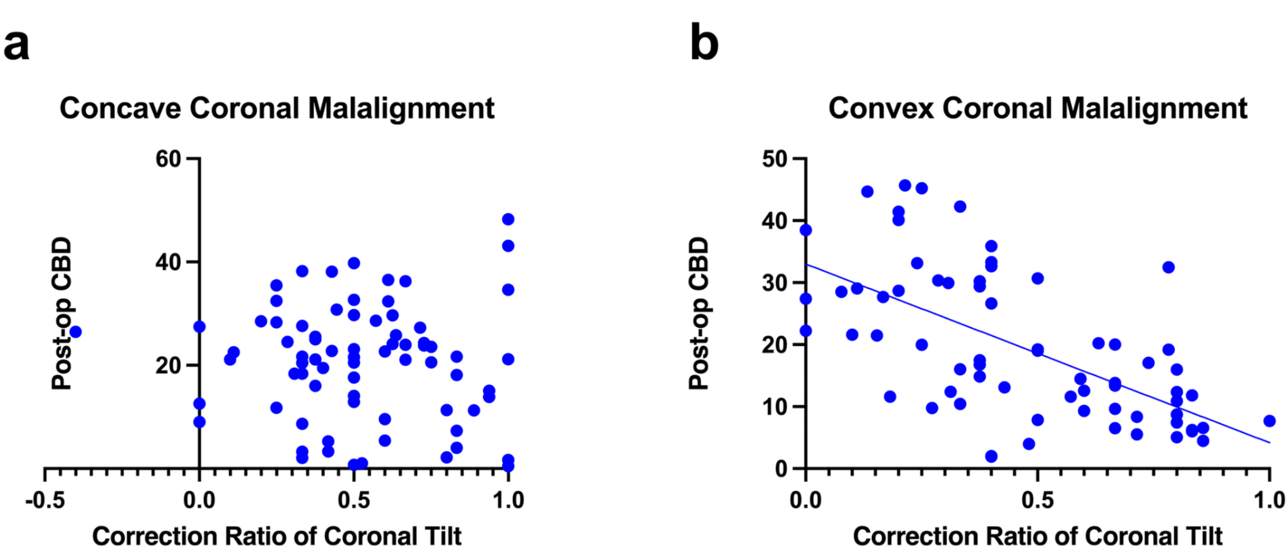

Fig. 1 The relationship between postoperative CBD and correction ratio of coronal tilt at L4/L5 in concave coronal malalignment (**a**) and convex coronal malalignment (**b**)

Table 4 Operation time and blood loss

	Operation Time (min)	*P* value	Blood loss (mL)	*P* value
Long-segment fusion				
Concave-L	261.59 ± 61.81	0.632	771.95 ± 277.95	0.650
Convex-L	255.74 ± 45.91		805.13 ± 369.89	
Short-segment fusion				
Concave-S	149.39 ± 28.47	0.234	249.7 ± 84.61	0.473
Convex-S	142 ± 19.6		233.87 ± 90.73	

Table 5 VAS score before and after surgery

	Pre-op	Post-op	*P* value
Concave-L	5.27 ± 1.9	1.41 ± 1.1	< 0.001
Concave-S	5.52 ± 1.54	1.42 ± 1	< 0.001
Convex-L	5.46 ± 1.8	1.51 ± 1.25	< 0.001
Convex-S	5.16 ± 1.53	1.19 ± 0.87	< 0.001
P value between groups	0.817	0.663	

type 2 or Qiu type C). Clinically, in convex-type cases, inadequate correction of the lumbosacral curve despite sufficient correction of the thoracolumbar curve may exacerbate coronal imbalance. For complex convex adult spinal deformities, Bao et al. [16] proposed a sequential correction technique, which decomposes complex deformity correction into three steps using multiple short and long rods with distinct functions: "lumbosacral compression at convexity + distraction of lumbosacral curve at concavity + integration." In addition to complex scoliosis, there are also numerous cases of degenerative scoliosis in clinical practice, often accompanied by milder coronal imbalance and concave-sided radiculopathy, without necessitating three-column osteotomy. We have observed that a subset of these cases can achieve effective coronal rebalance through short-segment lumbosacral fixation, and the degree of lumbosacral vertebral leveling serves as a predictor for postoperative CBD.

This study evaluated the effectiveness of long-segment and short-segment fusion treatments on these imbalances. In the concave group, long-segment fusion improved all coronal plane parameters, whereas short-segment fusion improved the Cobb angle and maximum coronal tilt angle but did not rectify the coronal plane imbalance. Thus, we posit that the initiating factor of concave malalignment likely originates from the main curve, and correcting only the lumbosacral curve may alleviate radicular symptoms but does not fully correct the coronal plane imbalance. Conversely, in the convex group, both long-segment and short-segment fusion is effective in achieving good postoperative coronal plane balance, indicating that the initiating factor of convex malalignment likely originates from the lumbosacral curve, and correcting the lumbosacral curve with short-segment fusion effectively corrects the coronal plane imbalance. It should be noted that our inclusion criteria required that the fusion construct included at least two vertebrae in the lumbosacral region (L4–S1). Therefore, the term "short-segment fusion" in our study actually refers to "lumbosacral curve fusion". We hope this finding draws more attention to the role of lumbosacral correction in restoring coronal balance in convex malalignment cases, particularly in elderly patients with poor baseline conditions. For these patients, when lumbosacral correction is sufficient, extensive fusion can sometimes be avoided, thereby reducing unnecessary surgical morbidity and complications. However, we emphasize that the selection of fusion levels should always be individualized. The length of fusion and surgical strategy should be determined based on a comprehensive assessment, including patient symptoms, the identification of pain generator, and the stiffness of compensatory curve.

The leveling of the L4 and L5 vertebrae in the lumbosacral region is crucial for correcting the lumbosacral curve (Fig. 2). The tilt angle of the L4 and L5 vertebrae has been shown to be a significant factor influencing immediate postoperative coronal imbalance [17]. However, no studies have yet reported a specific target range for the correction of coronal tilt in the lumbosacral curve to provide more precise intraoperative guidance. We found that achieving optimal postoperative coronal balance is not related to the absolute angle of vertebral tilt but rather to the correction ratio. This study proposes the correction rate of the lumbosacral curve's tilt (defined as the change in the maximum tilt angle of the L4 or L5 vertebra) as a objective measure of correction, and utilizes this metric to predict the necessary range of correction required to achieve an ideal postoperative coronal balance. For convex malalignment, when the maximum coronal tilt correction rate of L4 or L5 exceeds 45%, the postoperative CBD can be corrected to less than 2 cm (Fig. 3). This further indicates that the initial factor of convex malalignment originates from the lumbosacral curve, and when this curve is corrected, the coronal imbalance is also

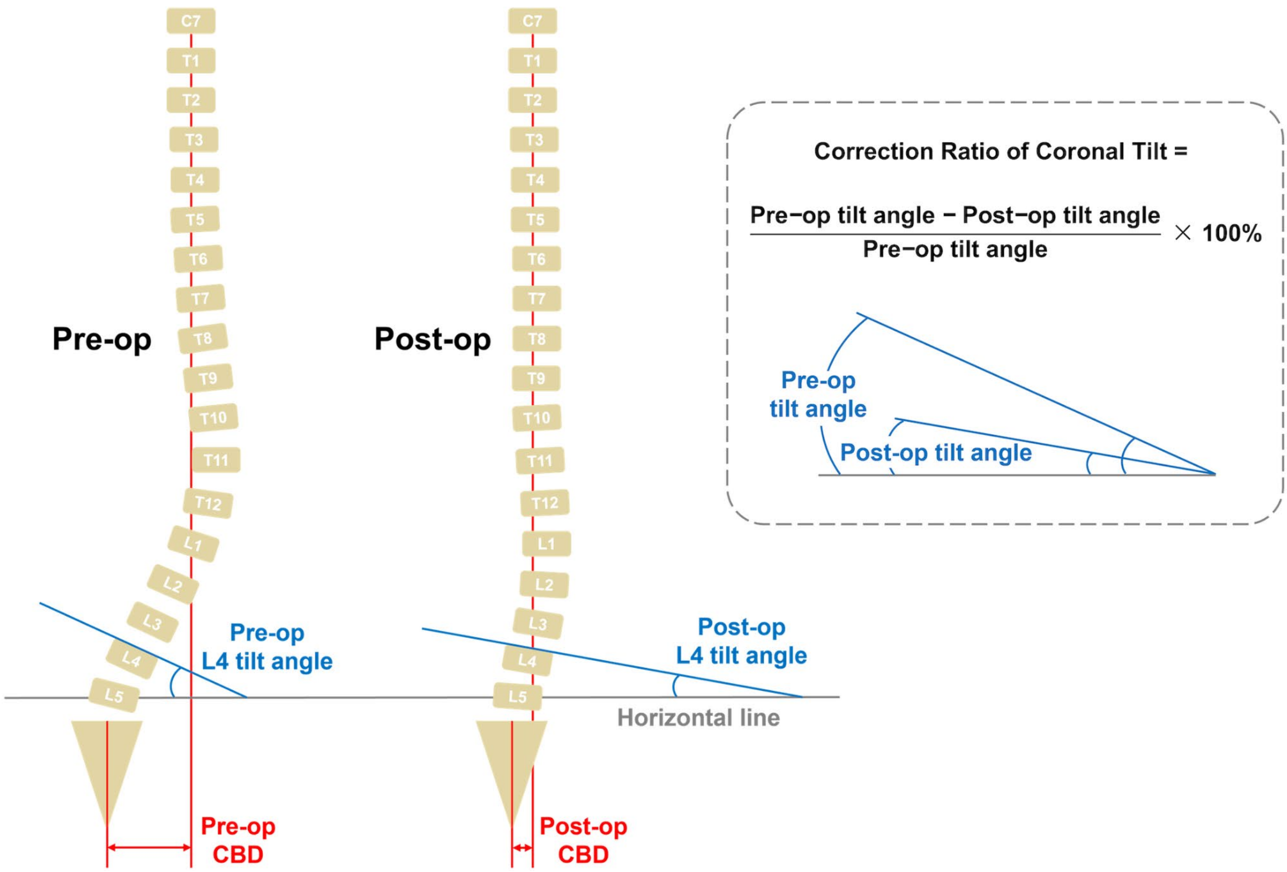

Fig. 2 Schematic representation of correcting coronal imbalance and CBD by leveling lumbosacral curve vertebral body

resolved. In contrast, in cases of concave malalignment, there is no significant correlation between postoperative CBD and the maximum coronal tilt of the lumbosacral curve, suggesting that achieving optimal postoperative balance through correction of the lumbosacral curve alone is challenging. Notably, it is critical to emphasize that this threshold was established based on our specific patient cohort. In clinical practice, some patients may require more individualized correction targets. Future studies with larger and more diverse populations are warranted to further refine these standards.

In addition to the primary focus of this study on surgical strategies and lumbosacral tilt correction, it is important to consider additional factors that may modulate postoperative coronal balance outcomes. Recent systematic reviews and meta-analyses have demonstrated that convex coronal malalignment and increased preoperative SVA are associated with a heightened risk of postoperative imbalance [18]. Furthermore, factors such as higher preoperative apical vertebral translation, preoperative Cobb angle, and tilt of the immediate postoperative upper instrumented vertebra have been shown to correlate with long-term sustainability of CBD [19]. Notably, preoperative paraspinal muscle condition also plays a critical role in maintaining coronal balance. Severe degeneration of the extensor muscles, as well as pronounced asymmetrical degeneration of the bilateral paraspinal muscles, has emerged as a potential risk factor for both persistent and recurrent coronal imbalance [20]. However, the causal relationship between these factors and postoperative CBD remains uncertain, and further research is needed.

This study has several limitations that should be acknowledged. First, its retrospective design and relatively small sample size may limit the generalizability of the findings. Additionally, the absence of long-term follow-up and comprehensive clinical symptom evaluation constrains the ability to assess the sustained impact of the surgical strategies discussed. These limitations underscore the need for further research, including larger, multicenter studies with extended follow-ups, with a particular focus on long-term imbalance, to validate these observations and refine treatment guidelines for ADS.

Conclusion

In summary, both short-segment and long-segment fusion can correct coronal imbalance in patients with convex malalignment classified by the Obeid

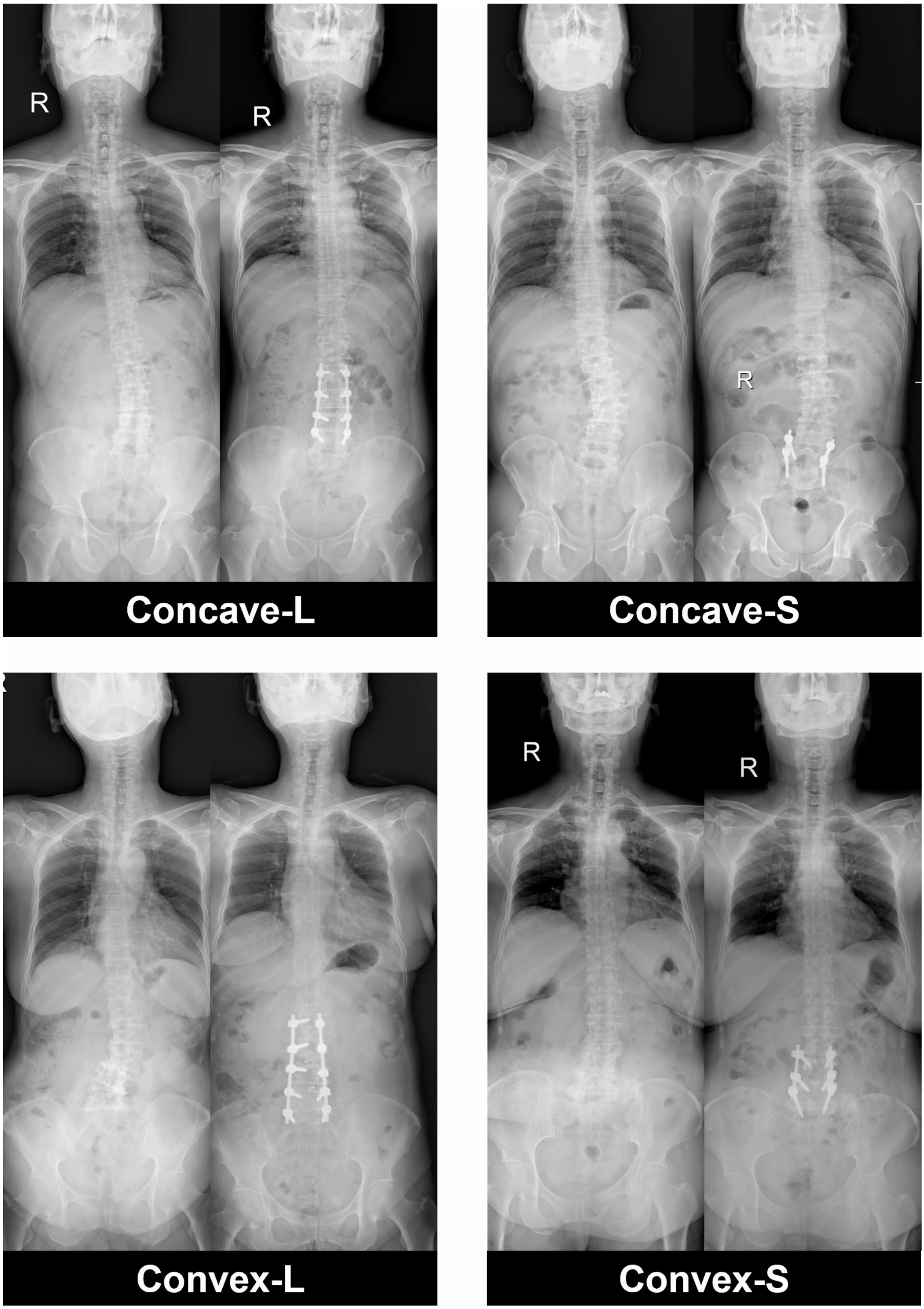

Fig. 3 Anteroposterior X-ray images of the Concave-L, Concave-S, Convex-L, and Convex-S cases before and after surgery

classification in ADS, while patients with concave malalignment require long-segment fusion to correct coronal imbalance. This study obtained predicted values through regression equations, suggesting that for better postoperative coronal balance, the correction ratio of the coronal maximum tilt of L4 or L5 vertebrae in patients with convex malalignment should exceed 45%.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12891-025-08655-3.

Supplementary Material 1

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Author contributions

ZJ, ZL, CL contributed equally to this work and should be considered co-first authors.Conceptualization: ZJ, ZL, XF, RZ; Data curation: ZL, CL, XW, LL, YC; Formal analysis: MZ; Methodology: ZL; Project administration: XF, WD, RZ; Visualization: HY; Writing - original draft: ZJ, CL; Writing - review & editing: ZL, XF, RZ.

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Data availability

The datasets generated and/or analyzed during the current study are not publicly available but available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

The study conformed to the Declaration of Helsinki and was approved by the Ethics Committee of Tianjin Union Medical Center (Medical Ethical Review No. 2024B104), with informed consent obtained from all participants. Clinical trial number: not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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