European Spine Journal (2019) 28:2042–2052
https://doi.org/10.1007/s00586-019-06019-9

ORIGINAL ARTICLE

Immediate postoperative coronal imbalance in Lenke 5 and Lenke 6 adolescent idiopathic scoliosis: Is it predictable?

Kai Chen[1] · Jinyi Bai[1] · Yilin Yang[1] · Jie Shao[1] · Mingyuan Yang[1] · Jian Zhao[1] · Changwei Yang[1] · Ming Li[1]

Received: 21 January 2019 / Revised: 10 May 2019 / Accepted: 24 May 2019 / Published online: 30 May 2019

Abstract

Purpose Immediate postoperative coronal imbalance (IPCIB) is a common reason for worse postoperative appearance in adolescent idiopathic scoliosis (AIS) patients and rarely improves on its own at follow-up, thereby greatly influencing the patients' health-related quality of life. However, no studies have been performed to detect the primary risk factors for IPCIB and it remains unclear whether the condition can be predicted preoperatively. The purpose of this study is to detect the primary risk factors for IPCIB in Lenke 5 and Lenke 6 AIS patients and to explore whether IPCIB can be predicted preoperatively.

Methods Medical records of Lenke 5 and Lenke 6 AIS patients who underwent correction surgery in our hospital from June 2017 to October 2018 were analyzed. Anteroposterior films were evaluated before and after surgery. Patients were divided into two groups, i.e., occurrence and non-occurrence of IPCIB. The risk factors for IPCIB were analyzed, and an IPCIB index was proposed and verified.

Results Thirty-seven Lenke 5/Lenke 6 AIS patients with IPCIB and 48 patients without IPCIB were recruited. Univariate analysis showed that there were significant differences between the two groups in the number of unfused vertebrae, preoperative thoracic Cobb angle, preoperative lumbar Cobb angle, preoperative translation of lumbar apex, preoperative coronal balance, preoperative L5 tilt, preoperative bending L5 tilt, postoperative translation of thoracic apex, postoperative lumbar Cobb angle, postoperative translation of lumbar apex, postoperative radiographic shoulder height, and postoperative L5 tilt. Logistic regression analysis showed that the preoperative bending L5 tilt, postoperative translation of the thoracic apex, and postoperative lumbar Cobb angle were the primary risk factors for IPCIB. The IPCIB index was defined as 1.3 * preoperative bending L5 tilt + 1.5 * postoperative translation of thoracic apex − 0.8 * postoperative lumbar Cobb angle. The receiver operating characteristics curve indicated that the occurrence rate of IPCIB was 88% and the non-occurrence rate was 90% when the IPCIB index was greater than 16.

Conclusion The preoperative bending L5 tilt, postoperative translation of the thoracic apex, and the postoperative lumbar Cobb angle were the primary risk factors for IPCIB in Lenke 5 and Lenke 6 AIS patients. The IPCIB index can be used to predict the occurrence of IPCIB with high accuracy. Our results indicate that the thoracic curve should be adequately corrected during surgery; however, moderate correction of the lumbar curve is recommended.

Kai Chen, Jinyi Bai, Yilin Yang and Jie Shao contributed equally to this work.

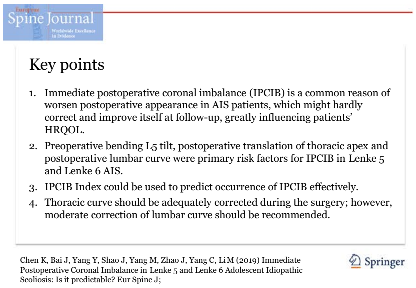
Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00586-019-06019-9) contains supplementary material, which is available to authorized users.

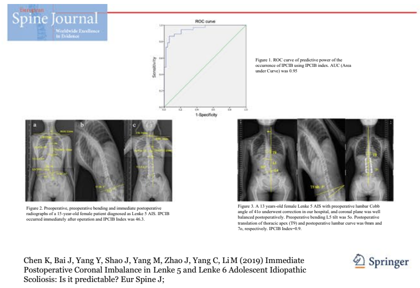
✉ Mingyuan Yang
yangmingyuan0330@163.com

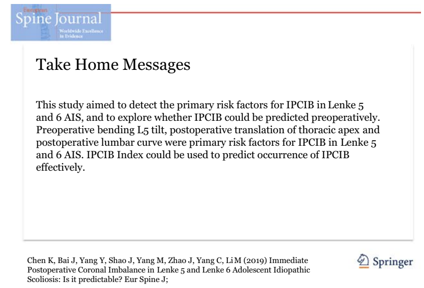
✉ Ming Li
limingspine0103@163.com

[1] Department of Orthopaedics, Changhai Hospital, Second Military Medical University, Shanghai, People's Republic of China

Graphic abstract These slides can be retrieved under Electronic Supplementary Material.







Keywords Adolescent idiopathic scoliosis · Immediate postoperative coronal imbalance · Lenke 5 and Lenke 6 AIS · Risk factors · Coronal balance

Introduction

Adolescent idiopathic scoliosis (AIS) is the most common type of spinal deformity in children between the ages of 11 and 18; it is characterized by a three-dimensional deformity including the coronal curves, sagittal alignment abnormalities, and axial rotation [1].

In 2002, Lenke et al. [2] introduced a new classification of AIS that helped spine surgeons to determine the extent of spinal instrumentation [3]. In Lenke's classification, type 5 scoliosis and type 6 scoliosis are characterized by a thoracolumbar or lumbar (TL/L) curve with a non-structural or structural main thoracic curve. For these two types, recommended instrumentation for fusion should include the structural TL/L curve as well as structural main thoracic curve in Lenke 6 AIS. However, compared with other types of AIS, a large portion of patients with Lenke 5 and Lenke 6 AIS show postoperative coronal imbalance and numbers ranging from 12.5 to 50% have been reported in the formal literature [4–6]; these effects greatly influence the patients' postoperative appearance and their satisfaction with the surgery.

Immediate postoperative coronal imbalance (IPCIB) is regarded as a common reason for influencing Lenke 5 and Lenke 6 AIS patients' postoperative appearance and satisfaction to surgery with high incidence of 14.8% to 47.6% [7, 8]. Compared with other Scoliosis Research Society questionnaire (SRS-22) domains, AIS patients that focus more on their postoperative appearance are less satisfied with the surgery [9]. In addition, our previous study verified that there is still a portion of AIS patients with IPCIB at the last follow-up [10], which was consistent with the results of other studies [7, 8, 11], suggesting that IPCIB does not improve on its own at follow-up. Thus, to improve patients' health-related quality of life (HRQOL), especially in terms of postoperative appearance and satisfaction with surgery, the restoration of coronal balance and the prevention of IPCIB are essential; this topic requires the attention of surgeons.

To restore the coronal balance after correction surgery and prevent the occurrence of postoperative coronal imbalance, some studies have been performed to detect the risk factors for postoperative coronal balance; however, these studies provided conflicting results [4, 12, 13]. Furthermore, these studies focused on postoperative coronal imbalance at the final follow-up rather than IPCIB, which is an important factor affecting the patients' satisfaction with the surgery. Therefore, there has been no consensus on the main causes and risk factors of IPCIB in Lenke 5 and Lenke 6 AIS patients after correction surgery and it remains unclear whether IPCIB can be predicted. The aim of this study is to detect the primary risk factors for IPCIB in Lenke 5 and Lenke 6 AIS patients. In addition, an IPCIB index is proposed and verified to ascertain whether IPCIB can be predicted.

Methods and materials

Patient population

Lenke 5 and Lenke 6 AIS patients who underwent all-pedicle screw instrumentation in our hospital from June 2017 to October 2018 were recruited. The inclusion criteria were as follows: (1) AIS patients had Lenke 5 and Lenke 6 scoliosis and had no previous operation history. (2) All patients received posterior correction surgery with all-pedicle screw instrumentation and rod derotation. (3) Patients had follow-ups for at least 2 years. (4) Anteroposterior films were evaluated before and after surgery. (5) The demographics and radiological data were collected preoperatively and postoperatively. The exclusion criteria were as follows: (1) The patients exhibited other types of AIS, such as Lenke 1 and Lenke 2 AIS. (2) The patients exhibited other types of scoliosis, such as neuromuscular scoliosis and degenerative scoliosis. In addition, patients without sufficient radiological parameters were also excluded. This study was approved by the Institutional Review Board in our hospital, and all patients in our study provided written informed consent for the study.

Data collection and statistical analysis

The demographic data including age, gender, Risser sign, and Lenke type were recorded. The anteroposterior films were evaluated before and after surgery and at the final follow-up.

Radiological parameters were measured, including the lower end vertebra (LEV), upper instrumented vertebra (UIV), lower instrumented vertebra (LIV), LIV–LEV (the numbers of segments between LIV and LEV), fusion number, number of levels unfused (the number of vertebrae from the first non-fused vertebra to the L5 vertebra; for example, if the first unfused vertebra was L1, the number of the remaining segments was 5), preoperative and postoperative thoracic Cobb angles, preoperative and postoperative translation of thoracic apex [the distance between the apex vertebra of the thoracic curve and the center sacral vertical line (CSVL)], preoperative and postoperative rotation of thoracic apex (°) (evaluated using the Nash–Moe method [14]), preoperative and postoperative lumbar Cobb angles, preoperative and postoperative translation of lumbar apex (the distance between the apex vertebra of the lumbar curve and the CSVL), preoperative and postoperative rotation of lumbar apex (°), preoperative and postoperative radiographic shoulder height (RSH), the difference in the soft tissue shadow directly superior to the acromioclavicular joint on the standing anteroposterior radiographs), preoperative and postoperative coronal balance (the horizontal distance between the center of the S1 vertebra and a vertical line drawn from the center of C7 and C7-CSVL), preoperative and postoperative L5 tilt (the angle between the line connecting the middle point of two pedicles of L5 and the line connecting the highest point of the bilateral iliac crests), and the preoperative L5 tilt in the bending films.

The SRS-22 scores were also evaluated with regard to the patient-centered outcomes, including pain, appearance, activity, mental health, and satisfaction before and after surgery and at the final follow-up.

All the parameters were obtained by 2 independent surgeons with 2 repeats, and the average value of 4 measurements was calculated.

According to the definition of postoperative coronal imbalance (C7-CSVL > 20 mm) [7], patients were divided into two groups: IPCIB group (C7-CSVL ≥ 20 mm) and non-IPCIB group (C7-CSVL < 20 mm). Univariate analysis (independent 2-sample test and χ^2 test) was performed by comparing the demographic data and radiological parameters of the two groups. Binary logistic regression models with forward elimination (conditional) were constructed using variables that were found significant in the univariate analysis to determine the independent risk factors associated with IPCIB. Furthermore, an IPCIB index was developed according to the results of the logistic regression to create a novel predictor for IPCIB. The sensitivity and specificity of the predictive power of the occurrence of IPCIB of the proposed index were calculated, and the receiver operating characteristics (ROC) curve was created. In addition, the radiological parameters and SRS-22 scores immediately postoperative and at final follow-up were also compared. $P < 0.05$ was considered a significant difference.

Results

Demographic data and general information

A total of 85 Lenke 5 AIS ($n = 70$) and Lenke 6 AIS ($n = 15$) patients were recruited in our study. The mean age was 17.61, ranging from 11 to 35 years. The average Risser sign was 3.53, ranging from 0 to 5. The number of UIV for T3, T4, T5, T6, T7, T8, T9, T10, and T11 was 5, 11, 8, 6, 1, 3, 6, 20, and 10, respectively. The number of LIV for L3, L4, and L5 LIV was 25, 38, and 7, respectively. The mean segments of the LIV–LEV were − 0.04 (− 2 to 2). The number of fusion levels and unfusion levels were 9.72 (5–14) and 1.27 (0–2), respectively. No significant differences were observed in the 5 domains of the SRS-22 between the two groups before the surgery (pain: 2.32 ± 0.75 vs. 2.04 ± 0.90, $P = 0.126$; appearance: 3.70 ± 0.62 vs. 4.02 ± 1.16, $P = 0.134$; activity: 2.81 ± 0.78 vs. 3.02 ± 0.91, $P = 0.265$; mental health: 4.03 ± 0.80 vs. 4.17 ± 0.81, $P = 0.429$; satisfaction: 3.62 ± 0.49 vs. 3.42 ± 0.71, $P = 0.137$; total score: 3.30 ± 0.32 vs. 3.33 ± 0.42, $P = 0.665$). All the demographic data and radiological parameters are shown in Table 1.

Univariate analysis

Thirty-seven patients with IPCIB and 48 patients without IPCIB were included in the IPCIB group and non-IPCIB group, respectively. Our univariate analysis showed that there were fewer unfused segments in the IPCIB group than the non-IPCIB group (1.11 ± 0.66 vs. 1.40 ± 0.61, $P = 0.040$). Significant differences between the IPCIB group and non-IPCIB group were found for the following parameters: preoperative thoracic Cobb angle (19.65° ± 5.79° vs.

Table 1 Demographics and radiological parameters of recruited patients

Variables	Minimum	Maximum	Mean	SD
Demographics				
Age (years)	11	35	17.61	5.38
Gender	Female/male: 73/12			
Risser sign	0	5	3.53	1.55
Lenke type (Lenke 5/Lenke 6)	70/15			
LEV (L2/L3/L4/L5)	1/29/47/8			
UIV (T3/T4/T5/T6/T7/T8/T9/T10/T11)	5/11/8/6/1/3/6/20/10			
LIV (L3/L4/L5)	25/38/7			
LIV–LEV (segments)	– 2	2	– 0.04	0.85
Fusion number (segments)	5	14	9.72	2.90
Unfusion number (segments)	0	2	1.27	0.64
Preoperative parameters				
Preoperative thoracic curve (°)	1	57	22.31	10.20
Preoperative translation of thoracic apex (mm)	2	64	16.70	8.73
Preoperative rotation of thoracic apex (°)	0	2	0.53	0.63
Preoperative lumbar curve (°)	19	7	44.44	8.78
Preoperative translation of lumbar apex (mm)	9	73	49.91	12.28
Preoperative rotation of lumbar apex (°)	0	3	2.35	0.67
Preoperative RSH (mm)	– 22	26	1.13	13.39
Preoperative coronal balance (mm)	– 42	55	10.09	27.34
Preoperative L5 tilt (°)	– 24	23	9.75	7.11
Preoperative bending L5 tilt (°)	– 12	15	5.71	4.55
Postoperative parameters				
Postoperative thoracic curve (°)	1	51	13.62	7.60
Postoperative translation of thoracic apex (mm)	2	28	11.74	6.35
Postoperative rotation of thoracic apex (°)	0	1	0.22	0.42
Postoperative lumbar curve (°)	0	41	12.84	7.03
Postoperative translation of lumbar apex (mm)	4	57	18.38	7.91
Postoperative rotation of lumbar apex (°)	0	3	0.48	0.88
Postoperative RSH (mm)	– 21	25	8.02	9.33
Postoperative coronal balance (mm)	– 59	61	7.89	20.02
Postoperative L5 tilt (°)	– 13	18	6.60	4.61

24.35° ± 12.26°, $P = 0.034$), preoperative lumbar Cobb angle (46.86° ± 8.47° vs. 42.58° ± 8.64°, $P = 0.025$), preoperative translation of lumbar apex (54.19 ± 10.90 mm vs. 46.60 ± 12.38 mm, $P = 0.004$), preoperative coronal balance (22.65 ± 27.91 mm vs. 0.42 ± 22.79 mm, $P < 0.001$), preoperative L5 tilt (12.24° ± 6.53° vs. 7.83° ± 7.01°, $P = 0.004$), preoperative bending L5 tilt (8.16° ± 5.03° vs. 3.81° ± 3.04°, $P < 0.001$), postoperative translation of thoracic apex (16.27 ± 4.49 mm vs. 8.25 ± 5.29 mm, $P < 0.001$), postoperative lumbar Cobb angle (10.49° ± 6.93° vs. 14.65 ± 6.63°, $P = 0.006$), postoperative translation of lumbar apex (22.43 ± 7.78 mm vs. 15.25 ± 6.52 mm, $P < 0.001$), postoperative RSH (13.46 ± 8.80 mm vs. 3.83 ± 7.43 mm, $P < 0.001$), postoperative coronal balance (23.13 ± 26.12 mm vs. 0.77 ± 8.65 mm, $P < 0.001$), postoperative L5 tilt (7.89° ± 4.56° vs. 5.60° ± 4.44°, $P = 0.022$). However, we did not find any significant difference between the two groups in the age, gender, Risser sign, Lenke type, LEV, UIV, LIV, LIV–LEV, fused segments, preoperative translation of thoracic apex, preoperative rotation of thoracic apex, preoperative rotation of lumbar apex, preoperative RSH, postoperative thoracic Cobb angle, postoperative rotation of thoracic apex, and postoperative rotation of lumbar apex (all $P > 0.05$). The data are summarized in Table 2.

In addition, patients with IPCIB had worse scores of postoperative appearances (3.22 ± 0.75 vs. 4.50 ± 0.62, $P < 0.001$) and satisfaction with the surgery (3.03 ± 0.64 vs. 4.42 ± 0.77, $P < 0.001$) than patients without IPCIB; however, there were no significant differences in the scores of the other SRS-22 domains between the two groups (all $P > 0.05$, Table 2).

Table 2 Comparisons of demographics and radiological parameters between AIS with and without immediate postoperative coronal imbalance

Variables	Immediate postoperative Coronal imbalance ($n=37$)	Immediate postoperative Coronal balance ($n=48$)	*P* value
Demographics			
Age (years)	16.27 ± 6.3	17.10 ± 4.55	0.325
Gender (female/male)	34/3	39/9	0.162
Risser sign	3.16 ± 1.77	3.81 ± 1.30	0.054
Lenke type (Lenke 5/Lenke 6)	31/6	39/9	0.761
LEV (L2/L3/L4/L5)	0/15/17/5	1/14/30/3	0.287
UIV (T3/T4/T5/T6/T7/T8/T9/T10/T11)	5/7/2/3/1/1/5/8/5	7/9/6/5/0/2/1/13/5	0.540
LIV (L3/L4/L5)	10/21/6	22/23/3	0.120
LIV–LEV (segments)	0.11 ± 0.97	-0.15 ± 0.74	0.174
Fusion number (segments)	9.70 ± 3.04	9.73 ± 2.83	0.967
Unfusion number (segments)	**1.11 ± 0.66**	**1.40 ± 0.61**	**0.040**
Preoperative parameters			
Preoperative thoracic curve (°)	**19.65 ± 5.79**	**24.35 ± 12.26**	**0.034**
Preoperative translation of thoracic apex (mm)	15.19 ± 4.20	17.85 ± 10.93	0.164
Preoperative rotation of thoracic apex (°)	0.49 ± 0.61	0.56 ± 0.65	0.583
Preoperative lumbar curve (°)	**46.86 ± 8.47**	**42.58 ± 8.64**	**0.025**
Preoperative translation of lumbar apex (mm)	**54.19 ± 10.90**	**46.60 ± 12.38**	**0.004**
Preoperative rotation of lumbar apex (°)	2.43 ± 0.65	2.29 ± 0.68	0.338
Preoperative RSH (mm)	0.49 ± 12.61	1.63 ± 14.08	0.700
Preoperative coronal balance (mm)	**22.65 ± 27.91**	**0.42 ± 22.79**	**< 0.001**
Preoperative L5 tilt (°)	**12.24 ± 6.53**	**7.83 ± 7.01**	**0.004**
Preoperative bending L5 tilt (°)	**8.16 ± 5.03**	**3.81 ± 3.04**	**< 0.001**
Preoperative HRQOL			
Pain	2.32 ± 0.75	2.04 ± 0.90	0.126
Appearance	3.70 ± 0.62	4.02 ± 1.16	0.134
Activity	2.81 ± 0.78	3.02 ± 0.91	0.265
Mental health	4.03 ± 0.80	4.17 ± 0.81	0.429
Satisfaction	3.62 ± 0.49	3.42 ± 0.71	0.137
Total score	3.30 ± 0.32	3.33 ± 0.42	0.665
Postoperative parameters			
Postoperative thoracic curve (°)	13.54 ± 5.74	13.69 ± 8.84	0.930
Postoperative translation of thoracic apex (mm)	**16.27 ± 4.49**	**8.25 ± 5.29**	**< 0.001**
Postoperative rotation of thoracic apex (°)	0.22 ± 0.42	0.22 ± 0.42	0.889
Postoperative lumbar curve (°)	**10.49 ± 6.93**	**14.65 ± 6.63**	**0.006**
Postoperative translation of lumbar apex (mm)	**22.43 ± 7.78**	**15.25 ± 6.52**	**< 0.001**
Postoperative rotation of lumbar apex (°)	0.59 ± 1.07	0.40 ± 0.71	0.305
Postoperative RSH (mm)	**13.46 ± 8.80**	**3.83 ± 7.43**	**< 0.001**
Postoperative coronal balance (mm)	**23.13 ± 26.12**	**0.77 ± 8.65**	**< 0.001**
Postoperative L5 tilt (°)	**7.89 ± 4.56**	**5.60 ± 4.44**	**0.022**
Postoperative HRQOL			
Pain	4.59 ± 0.69	4.71 ± 0.71	0.461
Appearance	**3.22 ± 0.75**	**4.50 ± 0.62**	**< 0.001**
Activity	4.54 ± 0.61	4.46 ± 0.65	0.553
Mental health	4.32 ± 0.58	4.21 ± 0.58	0.364
Satisfaction	**3.03 ± 0.64**	**4.42 ± 0.77**	**< 0.001**
Total score	**3.94 ± 0.33**	**4.46 ± 0.31**	**< 0.001**

Bold values are statistically significant (*P* value < 0.05)

Multivariate analysis

We further performed a logistic regression analysis, and the results showed that preoperative bending L5 tilt (OR 1.32, 95% CI 1.08–1.63, $P=0.008$), postoperative translation of thoracic apex (OR 1.49, 95% CI 1.24–1.80, $P<0.001$), and postoperative lumbar Cobb angle (OR 0.80, 95% CI 0.70–0.91, $P=0.001$) were the primary risk factors for IPCIB; the other variables were not included in the regression equation (all $P>0.05$). The results of the logistic regression analysis are shown in Table 3. According to the regression equation, the IPCIB index is defined as 1.3 * preoperative bending L5 tilt + 1.5 * postoperative translation of thoracic apex − 0.8 * postoperative lumbar Cobb angle.

ROC curve

The ROC curve is shown in Fig. 1; the results showed that the area under the curve (AUC) was 0.95, suggesting that the effectiveness of the ROC curve for predicting the occurrence of IPCIB was good. Based on the ROC curve, the optimal cutoff value of the IPCIB index as indicators for the occurrence of IPCIB was 16. If the IPCIB index was greater than 16, the occurrence rate of IPCIB was 88% and the non-occurrence rate was 90%.

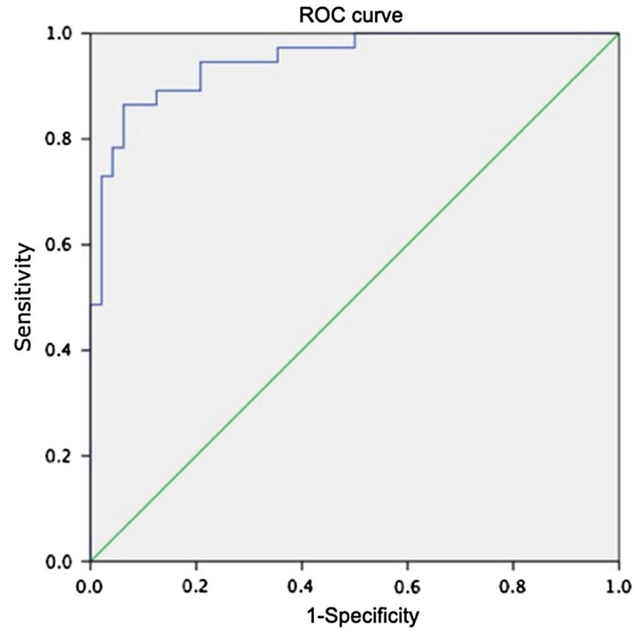


Fig. 1 ROC curve of predictive power of the occurrence of IPCIB using IPCIB index. Area under curve (AUC) was 0.95

Final follow-up

At the 2-year follow-up period, 11 AIS patients with IPCIB still exhibited coronal imbalance (11/85, 12.9%), whereas the remaining 26 patients who exhibited coronal imbalance immediately postoperative achieved balance at the final follow-up. Significant decreases in the postoperative translation of thoracic apex (11.46 ± 1.85 vs. 16.27 ± 4.49, $P<0.001$), postoperative translation of lumbar apex (14.32 ± 3.29 vs. 22.43 ± 7.78, $P<0.001$), postoperative RSH (7.54 ± 4.75 vs. 13.46 ± 8.80, $P<0.001$), postoperative coronal balance (10.57 ± 21.20 vs. 23.13 ± 26.12, $P<0.001$), and postoperative L5 tilt (5.14 ± 2.15 vs. 7.89 ± 4.56, $P<0.001$) were observed in the patients with IPCIB at final follow-up, whereas the thoracic curve (17.62 ± 3.38 vs. 13.54 ± 5.74, $P=0.002$) and lumbar curve (14.00 ± 5.80 vs. 10.49 ± 6.93, $P<0.001$) were significantly higher than compared to the immediate postoperative measurements. All the data are shown in Table 4.

The coronal alignment remained balanced in all patients without IPCIB at final follow-up without significant changes in the thoracic curve, translation of thoracic apex, rotation of thoracic apex, lumbar curve, translation of lumbar apex, rotation of lumbar apex, RSH, coronal balance, and L5 tilt (all $P>0.05$, Table 4).

In terms of the HRQOL, because the coronal alignments were balanced in most AIS patients with IPCIB at final follow-up, the scores of the appearance (4.08 ± 0.95 vs. 3.22 ± 0.75, $P<0.001$), satisfaction with the surgery (4.19 ± 1.02 vs. 3.03 ± 0.64, $P<0.001$), and total score (4.25 ± 0.34 vs. 3.94 ± 0.33, $P<0.001$) were significantly higher at final follow-up, whereas the scores of pain, activity, and mental health remained unchanged (all $P>0.05$,

Table 3 Logistic regression analysis of risk factors for immediate coronal imbalance in AIS

Variables	B	SE	Wald	*P* value	Exp (B)	95% CI	
						Lower	Upper
Preoperative bending L5 tilt	0.28	0.11	7.01	0.008	1.32	1.08	1.63
Postoperative translation of thoracic apex	0.40	0.10	17.69	< 0.001	1.49	1.24	1.80
Postoperative lumbar curve	-0.23	0.07	11.37	0.001	0.80	0.70	0.91
Constant	-3.75	1.19	9.98	0.002	0.02		

Table 4 Comparisons of radiological parameters and SRS-22 scores between immediate postoperation and final follow-up in patients with and without immediate postoperative coronal imbalance

Variables	Immediate postoperation	Final follow-up	*P* value
Immediate postoperative coronal imbalance (n = 37)			
Radiological parameters			
Postoperative thoracic curve (°)	**13.54 ± 5.74**	**17.62 ± 3.38**	**0.002**
Postoperative translation of thoracic apex (mm)	**16.27 ± 4.49**	**11.46 ± 1.85**	**< 0.001**
Postoperative rotation of thoracic apex (°)	0.22 ± 0.42	0.38 ± 0.49	0.136
Postoperative lumbar curve (°)	**10.49 ± 6.93**	**14.00 ± 5.80**	**< 0.001**
Postoperative translation of lumbar apex (mm)	**22.43 ± 7.78**	**14.32 ± 3.29**	**< 0.001**
Postoperative rotation of lumbar apex (°)	0.59 ± 1.07	0.46 ± 0.69	0.230
Postoperative RSH (mm)	**13.46 ± 8.80**	**7.54 ± 4.75**	**< 0.001**
Postoperative coronal balance (mm)	**23.13 ± 26.12**	**10.57 ± 21.20**	**< 0.001**
Postoperative L5 tilt (°)	**7.89 ± 4.56**	**5.14 ± 2.15**	**< 0.001**
HRQOL (SRS-22)			
Pain	4.59 ± 0.69	4.46 ± 0.73	0.376
Appearance	**3.22 ± 0.75**	**4.08 ± 0.95**	**< 0.001**
Activity	4.54 ± 0.61	4.24 ± 0.80	0.094
Mental health	4.32 ± 0.58	4.30 ± 0.78	0.845
Satisfaction	**3.03 ± 0.64**	**4.19 ± 1.02**	**< 0.001**
Total score	**3.94 ± 0.33**	**4.25 ± 0.34**	**< 0.001**
Immediate postoperative coronal balance (*n* = 48)			
Radiological parameters			
Postoperative thoracic curve (°)	13.69 ± 8.84	15.27 ± 5.81	0.072
Postoperative translation of thoracic apex (mm)	8.25 ± 5.29	9.08 ± 4.49	0.206
Postoperative rotation of thoracic apex (°)	0.22 ± 0.42	0.27 ± 0.45	0.159
Postoperative lumbar curve (°)	14.65 ± 6.63	13.63 ± 6.37	0.093
Postoperative translation of lumbar apex (mm)	15.25 ± 6.52	13.58 ± 4.60	0.114
Postoperative rotation of lumbar apex (°)	0.40 ± 0.71	0.29 ± 0.50	0.133
Postoperative RSH (mm)	3.83 ± 7.43	2.96 ± 5.39	0.180
Postoperative coronal balance (mm)	0.77 ± 8.65	0.42 ± 3.58	0.725
Postoperative L5 tilt (°)	5.60 ± 4.44	6.27 ± 3.73	0.431
HRQOL (SRS-22)			
Pain	4.71 ± 0.71	4.64 ± 0.60	0.584
Appearance	4.50 ± 0.62	4.33 ± 0.60	0.173
Activity	4.46 ± 0.65	4.23 ± 0.75	0.094
Mental health	4.21 ± 0.58	4.29 ± 0.74	0.543
Satisfaction	4.42 ± 0.77	4.27 ± 0.64	0.351
Total score	4.46 ± 0.31	4.35 ± 0.39	0.088

Bold values are statistically significant (P value < 0.05)

Table 4). For patients without IPCIB, no significant changes in the thoracic curve, translation of thoracic apex, rotation of thoracic apex, lumbar curve, translation of lumbar apex, rotation of lumbar apex, RSH, coronal balance, and L5 tilt were observed at final follow-up (all $P > 0.05$, Table 4). The results of the SRS-22 questionnaire indicated that the appearance and satisfaction with the surgery were associated with coronal imbalance; these were also the factors of greatest interest to the patients.

Typical cases

Typical case 1 is shown in Fig. 2 a, which shows the preoperative radiographs of a 15-year-old female patient diagnosed with Lenke 5 AIS with a Risser sign of 3. The preoperative thoracic Cobb angle (T6–T10) was 28°; the preoperative translation of thoracic apex (T8) was 12 mm; the preoperative rotation of thoracic apex (T8) was 1°; the preoperative lumbar Cobb angle (T11–L4) was 43°; the

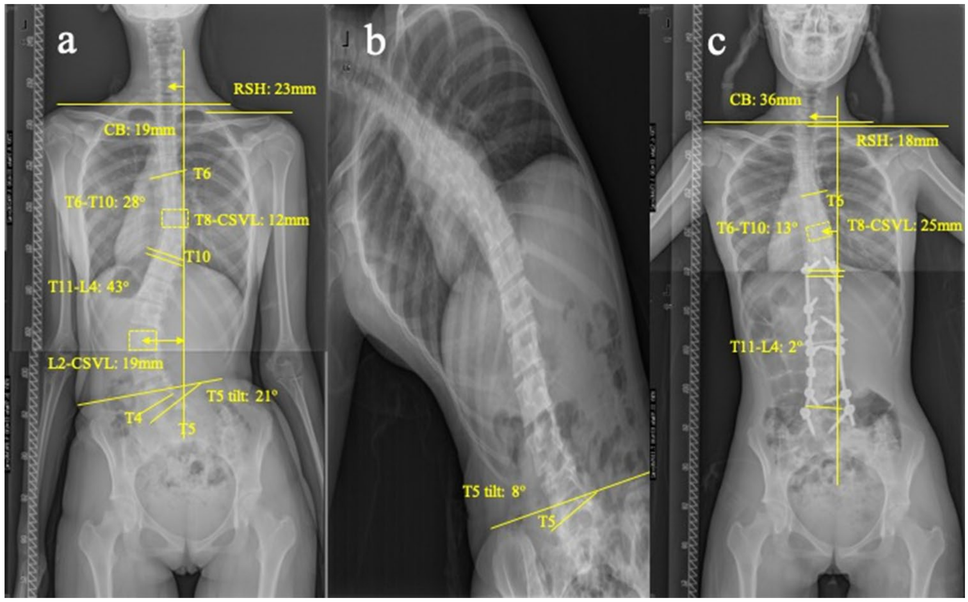


Fig. 2 Preoperative, preoperative bending and immediate postoperative radiographs of a 15-year-old female patient diagnosed as Lenke 5 AIS. IPCIB occurred immediately after operation, and IPCIB index was 46.3

preoperative translation of lumbar apex (L2) was 19 mm; the preoperative rotation of lumbar apex (T2) was 3°; the preoperative RSH was 23 mm; the preoperative coronal balance was 19 mm, and the preoperative L5 tilt was 21°. Figure 2 b shows the bending films; the preoperative bending L5 tilt had an angle of 8°. Figure 2 c shows the immediate postoperative follow-up results; IPCIB occurred with a postoperative coronal balance of 36 mm. The postoperative translation of thoracic apex (T8) and postoperative lumbar Cobb angle were 25 mm and 2°, respectively. The IPCIB index was $46.3 > 16$.

Another typical case is shown in Fig. 3. A 13-year-old female with Lenke 5 AIS with a preoperative lumbar Cobb angle of 41° underwent correction in our hospital, and the coronal plane was well balanced postoperatively. The preoperative bending L5 tilt was 5°. The postoperative translation of thoracic apex (T9) and postoperative lumbar Cobb angle were 0 mm and 7°, respectively. IPCIB index $= 1.3 * 5 + 1.5 * 0 - 0.8 * 7 = 0.9$.

Discussion

IPCIB is a common immediate radiological complication in Lenke 5 and Lenke 6 AIS patients who receive correction surgery. It has been reported that the incidence of IPCIB in Lenke 5/6 AIS patients is very high, ranging from 14.8 to 46.25% [7, 10, 15]. In Lenke 1C and 2C AIS patients, the incidence of IPCIB was reported to be as high as 47.6% [8]. Furthermore, although coronal balance in some Lenke 5/6

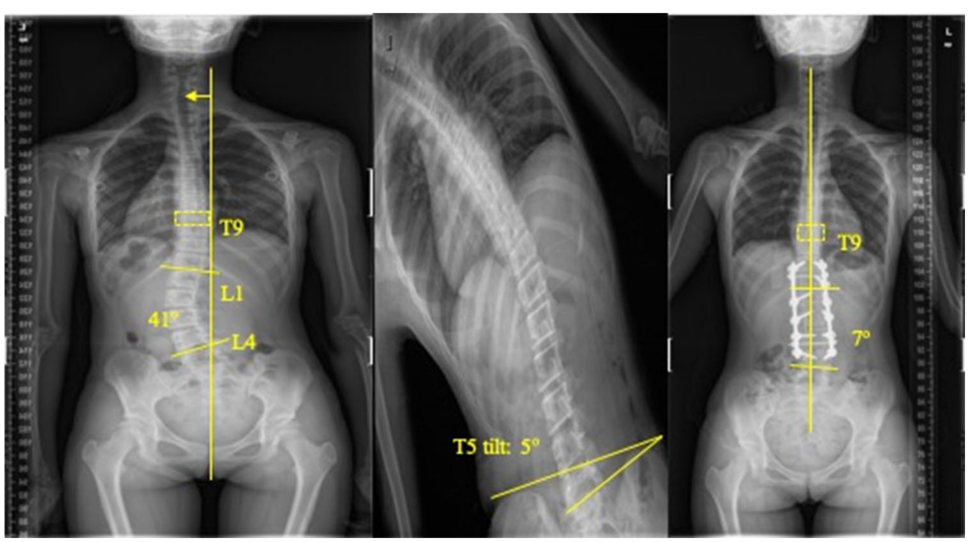


Fig. 3 A 13-year-old female Lenke 5 AIS with preoperative lumbar Cobb angle of 41° underwent correction in our hospital, and coronal plane was well balanced postoperatively. Preoperative bending L5 tilt was 5°. Postoperative translation of thoracic apex (T9) and postoperative lumbar curve was 0 mm and 7°, respectively. IPCIB index = 0.9

AIS patients with IPCIB might correct and improve itself at follow-up, a large portion of these patients still exhibit coronal imbalance at the last follow-up [4, 7, 8, 10].

In addition to a high incidence, IPCIB also leads to significant changes in the postoperative appearance, resulting in adverse impacts on the patients' HRQOL. The SRS-22 questionnaire results showed that patients with IPCIB had worse scores of appearance and satisfaction with the surgery than patients without IPCIB, suggesting that the restoration of the coronal balance and the prevention of IPCIB were key factors affecting the patients' postoperative HRQOL and the satisfaction with the surgery.

Therefore, it is essential to determinate the risk factors for IPCIB to prevent the occurrence of this complication and improve the patients' postoperative HRQOL. However, some studies have reported conflicting results [4, 7, 8] and it also remains unclear whether IPCIB can be predicted. Therefore, we determined the primary risk factors for IPCIB in Lenke 5 and Lenke 6 AIS patients and developed the IPCIB index to predict the rate of occurrence of postoperative coronal imbalance.

The univariate analysis results showed that the patients in the IPCIB group exhibited a smaller preoperative thoracic Cobb angle, larger preoperative lumbar Cobb angle, translation of lumbar apex, and coronal balance than patients without IPCIB, which was consistent with the results of other studies [4, 8]. There are several possible reasons why the Lenke 5/6 AIS patients with a larger preoperative lumbar Cobb angle, translation of lumbar apex, and coronal balance were more likely to suffer from IPCIB. First, a larger preoperative lumbar Cobb angle, translation of lumbar apex, and coronal balance are always accompanied by rigid scoliotic curves, which are difficult to correct during surgery, resulting in uncorrected scoliotic curves and postoperative coronal imbalance. Second, surgeons are more likely to choose long fusion segment instrumentation, which might increase the incidence of pelvic obliquity, finally leading to IPCIB. For patients with smaller thoracic curves, surgeons tend to select the lower thoracic vertebrae as UIV. As a result, the thoracic Cobb angle might increase with aging, leading to postoperative coronal imbalance. Our study also demonstrated the importance of selecting the UIV with regard to the occurrence and progression of postoperative coronal imbalance; this finding was consistent with those of Shetty et al. [7]. In their study, the authors suggested that increasing the UIV tilt might result in an improvement in coronal balance in the late follow-up period. Our results and those of Shetty et al. [7] indicate that there should be a greater focus on the selection of the UIV and correction of the thoracic curve in addition to focusing on the main TL/L scoliotic curve. Fewer unfused segments were observed in the IPCIB group than the non-IPCIB group, suggesting that the longer the fusion level, the more likely the occurrence of IPCIB was. The reason may be the pelvic obliquity caused by the long fusion segment instrumentation.

In terms of postoperative parameters, the postoperative translation values of the thoracic apex and lumbar apex were significantly greater in the IPCIB group than the non-IPCIB group. It is understandable that a greater postoperative translation of the thoracic apex and lumbar apex will cause postoperative coronal imbalance and inadequate restoration of the scoliotic curves might lead to postoperative coronal imbalance. Therefore, we recommend that adequate correction of the thoracic and lumbar curves should be restored to the CSVL. In addition, patients with IPCIB exhibited significantly larger postoperative RSH than patients without IPCIB. In our opinion, a significant shoulder imbalance might be a side effect of coronal imbalance. RSH is a common measurement to evaluate shoulder balance, and it is defined as the difference in the soft tissue shadow directly superior to the acromioclavicular joint in the standing anteroposterior radiographs. Therefore, a significant difference in the soft tissue shadow directly superior to the acromioclavicular joint is always observed in patients with IPCIB, leading to our findings.

In our previous study [10], we first included the L5 tilt, which is defined as the angle formed by the line connecting the middle point of the two pedicles of L5 and the line connecting the highest point of the bilateral iliac crest in the coronal view. We believed that the L5 tilt was a good parameter because the outline of the L5 is easy to identify and the L5 tilt might be an indicator of lumbosacral obliquity. Furthermore, our previous studies also indicated that the L5 tilt on bending films was an important risk factor for postoperative CIB in Lenke 5/6 AIS, which might be compensated by the way similar to that seen in the Lenke 1 distal adding-on phenomenon. The results of the univariate analysis and logistic regression analysis were consistent with our previous results, indicating that the larger the preoperative L5 tilt on the bending films, the more likely the occurrence of IPCIB was. As we mentioned before, the L5 tilt is an indicator of lumbosacral obliquity and the L5 tilt on the bending indicates the flexibility of the pelvis and ability of compensation of lumbosacral vertebrae. The results of the univariate analysis indicated that long fusion segments might result in IPCIB. We recommended an appropriate shortening of the fusion segments, which might reduce the occurrence of IPCIB in patients with a relatively large L5 tilt on the preoperative bending radiograph.

In addition, the multivariate analysis results showed that the postoperative translation of the thoracic apex and postoperative lumbar Cobb angle were also primary risk factors for the occurrence of IPCIB. The smaller the postoperative lumbar Cobb angle, the more likely the occurrence of IPCIB was, indicating that a moderate correction of the lumbar scoliotic curves should be performed rather than straightening of the lumbar scoliotic curves. The more straight the scoliotic curves were after correction, the less ability of compensation the lumbar had, leading to pelvis obliquity and coronal imbalance.

The regression equation of the IPCIB index was 1.3 * preoperative bending L5 tilt + 1.5 * postoperative translation of thoracic apex − 0.8 * postoperative lumbar Cobb angle. The results of the ROC curve analysis showed that the optimal cut-off value of the IPCIB index for predicting the occurrence of IPCIB was 16. If the IPCIB index was greater than 16, the occurrence rate of IPCIB was 88% and the non-occurrence rate was 90%. These findings suggested that IPCIB is predictable and the IPCIB index was suitable for this purpose.

Based on the findings of this study, we recommend the following: (1) A greater focus should be placed on the selection of the UIV and the correction of the thoracic curve in addition to the main TL/L scoliotic curve. (2) An adequate correction of the thoracic and lumbar Cobb angles, which should be restored to the CSVL, should be performed. (3) An appropriate shortening of the fusion segments might help reduce the occurrence of IPCIB in patients with a relatively large L5 tilt on the preoperative bending radiograph. (4) A moderate correction of the lumbar scoliotic curves should be performed rather than straightening the lumbar scoliotic curves.

In addition, we conducted follow-ups with the patients in this study for at least 2 years and found that most Lenke 5 and 6 AIS patients with IPCIB exhibited spontaneous correction during the follow-up; these results are consistent with those of Jiang et al. [16], Hwang et al. [13], and Ishikawa et al [8]. We attribute these outcomes to flexible unfused segments and shoulders and the coordinated compensation of the shoulders, spine, pelvis, and lower limbs. However, although most Lenke 5 and 6 AIS patients with IPCIB showed spontaneous correction during the follow-up, there was still a portion of Lenke 5 and 6 AIS patients with IPCIB whose coronal imbalance could not be restored at final follow-up, thereby influencing the patients' HRQOL. Therefore, the assessment of the risk factors for IPCIB in Lenke 5 and 6 AIS patients still requires further investigations for the following reasons: (1) Patients with IPCIB had worse SRS-22 scores, especially with regard to appearance and satisfaction with the surgery. (2) Not all the Lenke 5 and 6 patients with IPCIB showed spontaneous correction during follow-up; therefore, spinal surgeons should try their best to prevent IPCIB when treating Lenke 5 and 6 AIS patients to prevent the occurrence of coronal imbalance at final follow-up and to improve the patients' HRQOL. (3) Our study also suggested that patients with good immediate postoperative coronal balance did not exhibit coronal decompensation and coronal imbalance at final follow-up, demonstrating the importance of immediate postoperative restoration of coronal balance.

However, some limitations of this study should be addressed. First, we used the line connecting the iliac crest instead of a horizontal line as the reference for the L5 tilt since it was difficult to measure the horizontal line on the bending radiographs. Second, pelvic rotation is often observed in many AIS patients and it might result in asymmetry of the iliac contour on the anterior–posterior view. The asymmetry might have had an impact on the accuracy of our measurements. In addition, the sample size of our study was relatively small; thus, large-scale studies are required.

Conclusion

Preoperative bending L5 tilt, postoperative translation of the thoracic apex, and the postoperative lumbar Cobb angle were the primary risk factors for IPCIB in Lenke 5 and Lenke 6 AIS patients. The IPCIB index predicted the occurrence of IPCIB with high accuracy. The results indicate that the thoracic Cobb angle should be adequately corrected during surgery; however, we recommend a moderate correction of the lumbar Cobb angle. An appropriate shortening of the fusion segments might help reduce the occurrence of IPCIB in patients with a relatively large L5 tilt on the preoperative bending radiograph.

Acknowledgements This study was sponsored by Shanghai Sailing Program (19YF1447100).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Jada A, Mackel CE, Hwang SW, Samdani AF, Stephen JH, Bennett JT, Baaj AA (2017) Evaluation and management of adolescent idiopathic scoliosis: a review. Neurosurg Focus 43:E2. https://doi.org/10.3171/2017.7.focus17297
2. Lenke LG, Betz RR, Harms J, Bridwell KH, Clements DH, Lowe TG, Blanke K (2001) Adolescent idiopathic scoliosis: a new classification to determine extent of spinal arthrodesis. J Bone Jt Surg Am 83-a:1169–1181
3. Choudhry MN, Ahmad Z, Verma R (2016) Adolescent Idiopathic Scoliosis. Open Orthop J 10:143–154. https://doi.org/10.2174/1874325001610010143
4. Yang X, Hu B, Song Y, Liu L, Zhou C, Zhou Z, Feng G (2018) Coronal and sagittal balance in Lenke 5 AIS patients following posterior fusion: important role of the lowest instrument vertebrae selection. BMC Musculoskelet disord 19:212. https://doi.org/10.1186/s12891-018-2135-2
5. Wang Y, Bunger CE, Zhang Y, Wu C, Li H, Dahl B, Hansen ES (2013) Lowest instrumented vertebra selection for Lenke 5C

scoliosis: a minimum 2-year radiographical follow-up. Spine 38:E894–900. https://doi.org/10.1097/BRS.0b013e31829537be
6. Yang X, Liu L, Song Y, Zhou C, Zhou Z, Wang L, Wang L (2015) Pre- and postoperative spinopelvic sagittal balance in adolescent patients with lenke type 5 idiopathic scoliosis. Spine 40:102–108. https://doi.org/10.1097/brs.0000000000000685
7. Shetty AP, Suresh S, Aiyer SN, Kanna R, Rajasekaran S (2017) Radiological factors affecting post-operative global coronal balance in Lenke 5 C scoliosis. J Spine Surg (Hong Kong) 3:541–547. https://doi.org/10.21037/jss.2017.09.04
8. Ishikawa M, Cao K, Pang L, Fujita N, Yagi M, Hosogane N, Tsuji T, Machida M, Ishihara S, Nishiyama M, Fukui Y, Nakamura M, Matsumoto M, Watanabe K (2017) Onset and remodeling of coronal imbalance after selective posterior thoracic fusion for Lenke 1C and 2C adolescent idiopathic scoliosis (a pilot study). Scoliosis Spinal Disord 12:16. https://doi.org/10.1186/s13013-017-0123-1
9. Cheshire J, Gardner A, Berryman F, Pynsent P (2017) Do the SRS-22 self-image and mental health domain scores reflect the degree of asymmetry of the back in adolescent idiopathic scoliosis? Scoliosis Spinal Disord 12:37. https://doi.org/10.1186/s13013-017-0144-9
10. Yang C, Zhao Y, Zhai X, Li J, Zhu X, Li M (2017) Coronal balance in idiopathic scoliosis: a radiological study after posterior fusion of thoracolumbar/lumbar curves (Lenke 5 or 6). Eur Spine J 26:1775–1781. https://doi.org/10.1007/s00586-016-4844-2
11. Atici Y, Erdogan S, Akman YE, Mert M, Carkci E, Tuzuner T (2016) The surgical overcorrection of Lenke type 1 deformities with selective fusion segments: What happens to the coronal balance? Korean J Spine 13:151–156. https://doi.org/10.14245/kjs.2016.13.3.151
12. Hu B, Yang X, Yang H, Liu L, Chen P, Wang L, Zhu C, Zhou C, Song Y (2018) Coronal imbalance in lenke 5c adolescent idiopathic scoliosis regarding selecting the lowest instrumented vertebra: lower end vertebra versus lower end vertebra +1 in posterior fusion. World Neurosurg 117:e522–e529. https://doi.org/10.1016/j.wneu.2018.06.070
13. Hwang CJ, Lee CS, Kim H, Lee DH, Cho JH (2018) Spontaneous correction of coronal imbalance after selective thoracolumbar-lumbar fusion in patients with Lenke-5C adolescent idiopathic scoliosis. Spine J. doi: 10.1016/j.spinee.2018.03.013
14. Nash CL Jr, Moe JH (1969) A study of vertebral rotation. J Bone Jt Surg Am 51:223–229
15. Li J, Hwang SW, Shi Z, Yan N, Yang C, Wang C, Zhu X, Hou T, Li M (2011) Analysis of radiographic parameters relevant to the lowest instrumented vertebrae and postoperative coronal balance in Lenke 5C patients. Spine 36:1673–1678. https://doi.org/10.1097/BRS.0b013e3182091fba
16. Jiang H, Shao W, Xu E, Ji Z, Lin T, Meng Y, Ma J, Wang C, Gao R, Zhou X (2018) Coronal imbalance after selective posterior thoracic fusion in patients with Lenke 1 and 2 adolescent idiopathic scoliosis. Biomed Res Int 2018:3476425. https://doi.org/10.1155/2018/3476425