A retrospective study to reveal factors associated with postoperative shoulder imbalance in patients with adolescent idiopathic scoliosis with double thoracic curve

Choon Sung Lee, MD, PhD, Chang Ju Hwang, MD, PhD, Eic Ju Lim, MD, Dong-Ho Lee, MD, PhD, and Jae Hwan Cho, MD

Department of Orthopaedic Surgery, Asan Medical Center, University of Ulsan College of Medicine, Seoul, South Korea

OBJECTIVE Postoperative shoulder imbalance (PSI) is a critical consideration after corrective surgery for a double thoracic curve (Lenke Type 2); however, the radiographic factors related to PSI remain unclear. The purpose of this study was to identify the radiographic factors related to PSI after corrective surgery for adolescent idiopathic scoliosis (AIS) in patients with a double thoracic curve.

METHODS This study included 80 patients with Lenke Type 2 AIS who underwent corrective surgery. Patients were grouped according to the presence [PSI(+)] or absence [PSI(–)] of shoulder imbalance at the final follow-up examination (differences of 20, 15, and 10 mm were used). Various radiographic parameters, including the Cobb angle of the proximal and middle thoracic curves (PTC and MTC), radiographic shoulder height (RSH), clavicle angle, T-1 tilt, trunk shift, and proximal and distal wedge angles (PWA and DWA), were assessed before and after surgery and compared between groups.

RESULTS Overall, postoperative RSH decreased with time in the PSI(–) group but not in the PSI(+) group. Statistical analyses revealed that the preoperative Risser grade ($p = 0.048$), postoperative PWA ($p = 0.028$), and postoperative PTC/MTC ratio ($p = 0.011$) correlated with PSI. Presence of the adding-on phenomenon was also correlated with PSI, although this result was not statistically significant ($p = 0.089$).

CONCLUSIONS Postoperative shoulder imbalance is common after corrective surgery for Lenke Type 2 AIS and correlates with a higher Risser grade, a larger postoperative PWA, and a higher postoperative PTC/MTC ratio. Presence of the distal adding-on phenomenon is associated with an increased PSI trend, although this result was not statistically significant. However, preoperative factors other than the Risser grade that affect the development of PSI were not identified by the study. Additional studies are required to reveal the risk factors for the development of PSI.

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KEY WORDS adolescent idiopathic scoliosis; double thoracic curve; shoulder imbalance; proximal wedge angle; adding-on phenomenon; spine

ABBREVIATIONS AIS = adolescent idiopathic scoliosis; CCAD = clavicle chest cage angle difference; CSVL = central sacral vertical line; DWA = distal wedge angle; LIV = lower instrumented vertebra; MTC = middle thoracic curve; PSI = postoperative shoulder imbalance; PTC = proximal thoracic curve; PWA = proximal wedge angle; RSH = radiographic shoulder height; UIV = upper instrumented vertebra.

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CORRECTIVE surgery is considered the only definite treatment option for adolescent idiopathic scoliosis (AIS) in patients with a large curve ($> 50^\circ$). The standard for judging the success of corrective surgery depends on radiographic parameters and functional outcomes. Until now, although a scoring system for assessing functional outcomes in patients with deformity had been introduced, radiographic parameters have been frequently used to evaluate outcomes after surgery. In general, patients are satisfied if a balanced spine, correction of hump deformity, and balanced shoulders result from surgery. Self-esteem is also elevated with these positive morphological changes. Although a balanced spine or hump correction can be achieved through surgical treatment, including use of the rod derotation method or thoracoplasty, achieving shoulder balance is relatively unpredictable.

Although subjective shoulder balance is most important, it is hard to evaluate and achieve using conventional surgeries. Thus, radiographic shoulder balance is frequently evaluated instead of subjective shoulder balance and is also considered a critical consideration when judging the success of corrective surgery. Historically, recognizing the proximal thoracic curve (PTC) has been considered important, because coronal decompensation or postoperative shoulder imbalance (PSI) can result when the PTC is left unfused.^{7,8} Shoulder imbalance after surgery has been thought to be caused by the surgeon's failure to properly select the upper instrumented vertebra (UIV). Thus, previous studies examined the relationship between the upper level of instrumentation and PSI.^{3,5} However, controversial results in this regard have been reported in several previous studies. A few studies have also investigated other factors related to PSI,^{11,12} but no definite conclusions have been made.

Determining preoperative factors that predict PSI should be valuable in reducing the rate of PSI. In addition, correlation analysis between postoperative radiographic parameters and the occurrence of PSI might help enhance our understanding of this phenomenon. Thus, in this study, we aimed to identify the preoperative and postoperative radiographic parameters related to PSI after corrective surgery for AIS in patients with a double thoracic curve. The identification of these factors might help us identify possible causes of PSI and preventive methods.

Methods

This study included 80 patients who underwent corrective surgery for AIS with a double thoracic curve (Lenke Type 2) between January 2006 and December 2011 at our hospital. Patients with other types of idiopathic scoliosis and patients with less than 2 years of follow-up were excluded from the study. Demographic data, including sex, age, height, and weight, were obtained from the patients' electronic medical records. The radiographic data were obtained from whole-spine anteroposterior and lateral radiographs using the picture-archiving communication system at our institution. Plain radiographs were obtained with the patients in an upright standing position in both views and with their arms folded forward in the lateral views.

Each patient underwent posterior surgery using the rod

derotation method with pedicle screw fixation. Selection of the fusion level largely depended on the patient's Lenke classification. Pedicle screw constructs were used at every level for each patient. However, forgoing screw insertion was considered for the level at which the width of the pedicle was too narrow. Osteotomies were not performed regardless of the rigidity of the curve. Patients received regular follow-up examinations 1, 6, and 12 months after surgery and yearly thereafter. This study was approved by the institutional review board of our institution, which waived the requirement for informed consent because of the retrospective nature of the analysis.

Radiographic Assessment

The degrees of PTC and middle thoracic curve (MTC) were assessed before and after surgery using the Cobb angle method. The PTC/MTC ratio was also calculated. Coronal-plane trunk shift was defined as the distance between the C-7 plumb line and the central sacral vertical line (CSVL). Coronal-plane decompensation was defined as a trunk shift > 20 mm. Radiographic shoulder height (RSH) was defined as the difference between the horizontal lines passing both superolateral tips of the clavicles. The clavicle angle was defined as the angle between the line passing the highest points of both clavicles and the horizontal line. T-1 tilt was defined as the angle between the upper endplate of T-1 and the horizontal line. The clavicle chest cage angle difference was defined as the difference between the left and right clavicle chest cage angles.¹⁹ Risser grades¹⁶ were also measured preoperatively. The proximal wedge angle (PWA) and distal wedge angle (DWA) were assessed as the angle of coronal wedging in the disc space just proximal to the UIV or just distal to the lower instrumented vertebra (LIV), respectively. All radiographic measurements are summarized in Fig. 1.

Selective thoracic fusion was defined as a discontinuation of distal fusion at L-1 or higher. The adding-on phenomenon was defined as a progressive increase in the number of vertebrae included within the primary curve distally in combination with either an increase of > 5 mm in the deviation of the first vertebra below the instrumentation from the CSVL or an increase of $> 5^\circ$ in angulation of the first disc below the instrumentation.¹⁸

We defined PSI as positive when the absolute value of RSH was > 20 , 15, or 10 mm. Patients were stratified according to the presence [PSI(+)] or absence [PSI(-)] of PSI at the final follow-up examination. All radiographic parameters were measured by one rater (J.H.C.) who at the time had 5 years of experience performing spinal surgery.

Statistical Analysis

Demographic data and radiographic parameters were compared between the PSI(+) and PSI(-) groups using the Student t-test, chi-square test, or Fisher exact test. Changes in the radiographic parameters between the preoperative and postoperative periods were analyzed using the paired t-test. Serial changes in RSH during the follow-up period were compared between groups using repeated-measures ANOVA. Comparisons of the radiographic parameters according to UIV were also performed using the Student t-

FIG. 1. Measurements of radiographic parameters. **Left:** Preoperative radiograph showing Lenke Type 2 AIS with a 40° PTC (T1–T5) and 51° MTC (T6–T11). **Right:** Postoperative radiograph showing the correction of PTC to 23° and MTC to 17°.

test. The relationship between the adding-on phenomenon and PSI was assessed using the Fisher exact test. Multivariate logistic regression analysis was used to determine the radiographic factors related to PSI. As a sensitivity analysis, these analyses were performed repeatedly using the different criteria for PSI. Statistical analyses were performed using the Statistical Package for Social Sciences 21.0 software package (SPSS, Inc.); $p < 0.05$ indicates a statistically significant result. Mean values are presented $\pm$ SD.

Results

Demographic Data and Characteristics of Curves

Of the 80 patients enrolled in this study, 26 were male and 54 were female. Their mean age was 15.1 ± 2.7 years. The mean height of the patients was 161.3 ± 8.3 cm, and their mean weight was 50.0 ± 9.3 kg. The mean follow-up period was 40.0 ± 15.7 months. The specific Lenke types included were 2A– (27 patients), 2AN (28 patients), 2B– (12 patients), 2BN (7 patients), 2C– (3 patients), and 2CN (3 patients). The mean Cobb angles of the PTC and MTC were $40.5^\circ \pm 9.9^\circ$ and $56.4^\circ \pm 10.7^\circ$, respectively.

The mean RSH, clavicle angle, and T-1 tilt were -5.3 ± 9.4 mm, $-0.3^\circ \pm 1.6^\circ$, and $5.8^\circ \pm 4.7^\circ$, respectively. T-3 was the most frequently chosen UIV (47 patients), followed by T-4 (17 patients), T-2 (14 patients), T-1 (1 patient), and T-5 (1 patient). L-2 was the most frequently chosen LIV (34 cases), followed by L-1 (24 cases), L-3 (19 cases), T-12 (2 patients), and L-4 (1 patient).

Comparisons of the PSI(+) and PSI(–) Groups

The PSI was positive in 12 (15%) of 80 patients at the final follow-up when using the criterion of 20 mm. The proportions of patients with PSI increased to 22.5% (18 of 80) and 46.3% (37 of 80) when using the criteria of 15 and 10 mm, respectively.

Demographic data and preoperative radiographic parameters were compared between the PSI(+) and PSI(–) groups using different criteria (Table 1). No differences were found between these groups except in the degree of preoperative MTC and Risser grade. A Risser grade higher than 3 was found more frequently in the PSI(+) group. The RSH increased postoperatively in both groups. However, the RSH decreased from 10.6 mm 1 month after surgery

TABLE 1. Comparisons of demographic data and preoperative radiographic parameters between the PSI(+) and PSI(-) groups according to different criteria*

Demographic or Radiographic Parameter	SHD <20 mm (n = 68)	SHD ≥20 mm (n = 12)	p Value	SHD <15 mm (n = 62)	SHD ≥15 mm (n = 18)	p Value	SHD <10 mm (n = 43)	SHD ≥10 mm (n = 37)	p Value
Age (yrs)	15.1 ± 2.8	14.9 ± 1.8	0.799	15.1 ± 2.8	15.1 ± 2.1	0.937	15.3 ± 3.0	14.9 ± 2.2	0.513
Sex (M/F)	22:46	4:8	0.947	20:42	6:12	0.932	14:29	12:25	0.990
Height (cm)	161.5 ± 8.6	160.2 ± 6.4	0.635	161.4 ± 8.7	160.9 ± 6.9	0.818	162.3 ± 8.9	160.1 ± 7.6	0.232
Weight (kg)	49.5 ± 9.2	53.5 ± 9.7	0.215	49.5 ± 9.2	51.9 ± 10.0	0.345	49.5 ± 9.9	50.7 ± 8.7	0.571
PTC (°)	41.1 ± 10.3	37.2 ± 6.6	0.201	41.3 ± 10.4	38.0 ± 7.7	0.216	42.0 ± 11.3	38.8 ± 7.7	0.141
MTC (°)	57.5 ± 10.8	49.8 ± 7.3	0.021†	57.0 ± 10.4	54.2 ± 11.8	0.338	56.5 ± 10.3	56.2 ± 11.3	0.894
PTC/MTC ratio	0.72 ± 0.13	0.75 ± 0.10	0.456	0.73 ± 0.13	0.71 ± 0.12	0.718	0.74 ± 0.14	0.70 ± 0.11	0.156
RSH (mm)	-5.4 ± 9.7	-4.5 ± 8.1	0.748	-5.4 ± 9.6	-4.9 ± 9.2	0.831	-5.5 ± 9.8	-5.0 ± 9.1	0.818
Clavicle angle (°)	-0.3 ± 1.8	-0.3 ± 1.4	0.936	-0.3 ± 1.8	-0.3 ± 1.7	0.979	-0.3 ± 1.9	-0.2 ± 1.6	0.738
T-1 tilt (°)	5.7 ± 4.7	5.9 ± 4.6	0.893	6.0 ± 4.6	5.1 ± 5.0	0.477	6.3 ± 4.6	5.1 ± 4.7	0.219
Risser grade (≤2/≥3)	26/42	1/11	0.051	25/37	2/16	0.024†	16/27	11/26	0.481
CCAD (°)	11.5 ± 9.5	10.8 ± 7.6	0.805	11.0 ± 8.9	12.7 ± 10.6	0.499	9.7 ± 9.3	13.4 ± 8.9	0.073
Trunk shift (mm)	2.6 ± 12.9	-2.5 ± 12.9	0.230	2.7 ± 12.9	-1.1 ± 13.1	0.287	1.7 ± 12.3	1.9 ± 13.9	0.943
FU period (mos)	29.8 ± 15.7	31.1 ± 16.2	0.788	29.5 ± 15.8	31.5 ± 15.7	0.639	29.3 ± 17.0	30.7 ± 14.2	0.704

FU = follow-up; SHD = shoulder height difference.

* Data represent mean ± SD for continuous variables and number of patients for categorical variables.

† Statistically significant value.

to 6.7 mm at the final follow-up examination in the PSI(-) group ($p = 0.001$). This trend was not evident in the PSI(+) group (which changed from 23.0 to 24.0 mm in the same period; $p = 0.735$). The changes in RSH during the postoperative period (summarized in Table 2) were significantly different between the PSI(+) and PSI(-) groups according to repeated-measures ANOVA ($p < 0.001$).

One month after surgery, the PWA was larger in the PSI(+) group than in the PSI(-) group ($6.4^\circ \pm 4.9^\circ$ vs $3.2^\circ \pm 3.3^\circ$, respectively; $p = 0.005$). However, no difference was found in terms of DWA ($1.7^\circ \pm 2.5^\circ$ vs $2.4^\circ \pm 2.4^\circ$, respectively; $p = 0.354$). At the final follow-up, the same results were found for PWA and DWA. In addition, the radiographic parameters related to shoulder balance, such as RSH, clavicle angle, and T-1 tilt, were significantly different between the 2 groups. Furthermore, the PTC/MTC ratio was higher in the PSI(+) group than in the PSI(-) group (2.15 vs 1.59, respectively; $p = 0.022$). These differences decreased when the criterion was changed from 20 to 15 or 10 mm. Comparisons of the radiographic parameters at the final follow-up between these 2 groups according to these criteria are summarized in Table 3.

Effects of the Adding-On Phenomenon and UIV on PSI

The distal adding-on phenomenon was observed in 6 patients during the follow-up period. The relationships between the distal adding-on phenomenon and PSI are compared in Table 4. There were positive correlations between these 2 factors using the criteria of 20 and 15 mm ($p = 0.041$ and 0.021 , respectively). The LIVs for the patients with the adding-on phenomenon were L-1 in 3 patients, L-2 in 1 patient, and L-3 in 2 patients. No correlation was found between LIV and the adding-on phenomenon ($p = 0.405$). Preoperative and postoperative radiographic parameters are compared in Table 5 according to the UIV.

A large preoperative PTC and large T-1 tilt were related to selecting a higher fusion level (UIV = T-1 or T-2). Of the postoperative radiographic parameters, RSH and PWA were related to UIV. Radiographic shoulder height (4.3 vs 10.5 mm, respectively) and PWA (1.1° vs 4.2° , respectively) were lower in the group of patients with a higher fusion level (UIV = T-1 or T-2) than in the group of those with a lower fusion level.

Multivariate Analysis

A multivariate logistic regression analysis was conducted using 6 variables: Risser grade at the time of surgery, 3 postoperative radiographic parameters (PWA, T-1 tilt, and PTC/MTC ratio), UIV, and presence of the adding-on phenomenon. Of these 6 variables, Risser grade, postoperative PWA, and the PTC/MTC ratio were found to be related to PSI ($p = 0.048$, 0.028 , and 0.011 , respectively). Presence of the adding-on phenomenon also was found to be related to PSI, but it was not statistically significant ($p =$

TABLE 2. Changes in RSH during the postoperative follow-up periods in both groups*

FU Period	PSI(-) (n = 68)	PSI(+) (n = 12)	p Value
Preop†	-5.4 ± 9.7	-4.5 ± 8.1	0.748
1-mo postop	10.6 ± 9.4	23.0 ± 9.4	<0.001
6-mo postop	10.6 ± 10.1	17.1 ± 9.9	0.062
1-yr postop	8.7 ± 8.6	19.4 ± 10.2	0.001
Final FU	6.7 ± 7.1	24.0 ± 2.3	<0.001

* PSI was defined by the criteria of 20 mm. Data represent mean ± SD. PSI values represent millimeters.

† Negative value indicates that the right shoulder was more elevated than the left shoulder.

TABLE 3. Comparisons of radiographic parameters at final follow-up between the PSI(+) and PSI(-) groups according to different criteria*

Radiographic Parameter	SHD <20 mm (n = 68)	SHD ≥20 mm (n = 12)	p Value	SHD <15 mm (n = 62)	SHD ≥15 mm (n = 18)	p Value	SHD <10 mm (n = 43)	SHD ≥10 mm (n = 37)	p Value
PTC (°)	20.0 ± 7.2	21.4 ± 8.9	0.558	19.8 ± 7.2	21.7 ± 8.1	0.342	20.8 ± 7.8	19.6 ± 7.0	0.505
Correction rate of PTC (%)	50.6 ± 15.1	43.4 ± 16.1	0.137	51.3 ± 15.5	43.6 ± 13.5	0.061	49.9 ± 15.9	49.1 ± 14.9	0.804
MTC (°)	13.7 ± 5.4	11.2 ± 5.0	0.134	13.5 ± 5.4	12.6 ± 5.6	0.495	14.3 ± 5.6	12.2 ± 5.0	0.096
Correction rate of MTC (%)	75.9 ± 8.8	78.1 ± 7.4	0.420	76.0 ± 8.9	77.1 ± 7.8	0.624	74.5 ± 9.3	78.2 ± 7.4	0.051
PTC/MTC ratio	1.59 ± 0.66	2.15 ± 1.22	0.022†	1.59 ± 0.67	1.97 ± 1.07	0.067	1.56 ± 0.66	1.81 ± 0.90	0.154
RSH (mm)	6.7 ± 7.1	24.0 ± 2.3	<0.001‡	5.7 ± 6.7	21.6 ± 4.0	<0.001‡	3.6 ± 4.8	15.9 ± 8.4	<0.001‡
Clavicle angle (°)	1.5 ± 1.4	6.5 ± 6.7	<0.001‡	1.3 ± 1.3	5.3 ± 5.7	0.009‡	0.9 ± 1.1	3.8 ± 4.3	<0.001‡
T-1 tilt (°)	8.1 ± 4.3	11.6 ± 6.4	0.019‡	8.2 ± 4.2	10.2 ± 6.2	0.112	8.4 ± 4.4	8.9 ± 5.5	0.676
STF (yes/no)	22/46	4/8	0.947	20/42	6/12	0.932	17/26	9/28	0.148
Trunk shift (mm)†	-7.5 ± 8.9	-5.4 ± 8.8	0.463	-7.2 ± 8.9	-7.0 ± 9.1	0.934	-8.0 ± 9.1	-6.3 ± 8.7	0.385
PWA (°)	2.4 ± 2.8	5.2 ± 6.0	0.013‡	2.4 ± 2.8	4.5 ± 5.0	0.100	2.5 ± 3.0	3.3 ± 4.0	0.275
DWA (°)	2.4 ± 2.8	1.8 ± 2.2	0.523	2.5 ± 2.9	1.7 ± 1.9	0.310	2.5 ± 2.9	2.1 ± 2.6	0.458

STF = selective thoracic fusion.

* Data represent mean ± SD.

† Negative value indicates that the trunk was shifted to the left side.

‡ Statistically significant value.

0.089). Representative radiographs of patients showing the factors related to PSI are shown in Figs. 2–5.

Discussion

Shoulder imbalance after corrective surgery for AIS is regarded as a critical problem, especially in patients with a double thoracic curve. In most instances, the height of the right shoulder becomes lower than that of the left shoulder after surgery. Thus, if the left shoulder is elevated preoperatively, extra caution is required to prevent PSI.¹⁷ However, the benefits of PTC correction are debatable. In an earlier study, spontaneous correction of PTCs after MTC correction was reported.⁶ In another study, it was suggested that extending fusion to T-2 or T-3 was not needed for non-structural PTCs.³ However, the commonly recommended upper fusion level is T-2 for patients with AIS and a double thoracic curve. We did not extend proximal fusion to T-2 in many patients because it could not cause shoulder imbalance if the right shoulder was elevated preoperatively. We believed that stopping the fusion at T-3 would be enough if the PTC was not severe.

We aimed to serially demonstrate postoperative changes in shoulder balance and identify plausible radiographic factors related to PSI. In this analysis, we found that the difference in shoulder height decreased during the postoperative follow-up period. However, this spontaneous correction was not found in our PSI(+) group. In this group, shoulder height imbalance was maintained from the immediate postoperative period through to the final follow-up examination. Our data also suggest that the postoperative PWA, postoperative PTC/MTC ratio, and presence of the adding-on phenomenon are most likely to be factors related to PSI. In the PSI(+) group, the PWA increased postoperatively, which can aggravate T-1 tilt and shoulder imbalance. The increase in the PWA is thought to be caused by a compensation mechanism aimed at maintaining trunk balance in the coronal plane. In this study,

the PWA was also smaller when instrumentation was extended more proximally (Table 5), which can lead to trunk imbalance. However, we did not identify any positive relationship between trunk shift and UIV.

The postoperative PTC/MTC ratio might also be an important factor for the onset of PSI. Several studies have reported that PTC and MTC correction prevent PSI. Sufficient PTC correction that is matched with MTC correction has also been suggested to reduce PSI.¹³ It was also reported that shoulder balance did not sufficiently improve even after applying the direct vertebral rotation method, which means that less MTC correction is needed to achieve better shoulder balance.² The results of our study are consistent with the findings of these previous studies.

The Risser grade is an indicator of maturity and is also associated with curve flexibility. If the Risser grade is higher, the ability to compensate for a shoulder imbalance might be reduced, which may underpin the observed correlation between the Risser grade and PSI.

The adding-on phenomenon is a frequently noted complication after inadequate LIV selection.¹⁰ Two studies addressed the relationship between this phenomenon and

TABLE 4. Comparisons of distal adding-on phenomenon between the PSI(+) and PSI(-) groups according to different criteria

SHD (mm)	Adding-On Phenomenon			p Value
	Not Seen	Seen	Total	
≥20	65	3	68	0.041*
<20	9	3	12	
≥15	60	2	62	0.021*
<15	14	4	18	
≥10	42	1	43	0.090
<10	32	5	37	

* Statistically significant value.

TABLE 5. Comparisons of preoperative and postoperative radiographic parameters according to the upper instrumented vertebra*

Radiographic Parameter	UIV Before Surgery		p Value	UIV After Surgery		p Value
	T1–2 (n = 15)	T3–5 (n = 65)		T1–2 (n = 15)	T3–5 (n = 65)	
PTC (°)	46.7 ± 13.6	39.1 ± 8.3	0.006	18.5 ± 5.4	20.7 ± 7.8	0.305
MTC (°)	58.1 ± 10.9	56.0 ± 10.7	0.480	13.0 ± 5.1	13.4 ± 5.5	0.798
RSH (mm)†	-3.4 ± 11.0	-5.7 ± 9.1	0.378	4.3 ± 8.4	10.5 ± 8.9	0.017
Clavicle angle (°)‡	-0.4 ± 2.3	-0.3 ± 1.6	0.785	1.3 ± 1.6	2.4 ± 3.6	0.255
T-1 tilt (°)	8.1 ± 5.2	5.2 ± 4.4	0.032	8.1 ± 3.5	8.8 ± 5.0	0.644
Trunk shift (mm)§	-0.9 ± 10.5	2.5 ± 13.5	0.369	-9.0 ± 9.4	-6.8 ± 8.8	0.385
PWA (°)	—	—	—	1.1 ± 1.6	4.2 ± 3.9	0.005
DWA (°)‡	—	—	—	1.9 ± 2.4	2.4 ± 2.5	0.477

* Data represent mean ± SD.

† Negative value indicates that the right shoulder is more elevated than the left shoulder.

‡ Negative value indicates that the right clavicle is more elevated than the left clavicle.

§ Negative value indicates that the trunk is shifted to the left.

PSI. In one of these study reports, the clavicle angle was reported to be smaller in patients with the distal adding-on phenomenon, which means that the adding-on phenomenon could be a compensation mechanism for PSI.¹¹ However, this result did not reach statistical significance ($p = 0.09$) and was confined to those with a Lenke 1A curve. It was reported from the other study that the adding-on phenomenon was significantly less common in the shoulder-imbalance group of patients with a Lenke Type 2 curve.¹ The authors suggested that both PSI and the adding-on

phenomenon need to be prevented. However, on the basis of our results, this recommendation should be reevaluated, although the number of patients with the adding-on phenomenon was too small to suggest that this phenomenon was not a compensation mechanism for PSI.

T-1 tilt has been thought to be another factor that is possibly related to PSI. Although most patients with a double thoracic curve had a positive T-1 tilt, it was not correlated with PSI in our series, which is consistent with the results of other studies.^{7,9} However, additional studies are required

FIG. 2. Left: Preoperative radiograph of a 13-year-old girl showing well-balanced shoulders with a 32° PTC and 44° MTC. **Right:** Postoperative radiograph 4 years after surgery showing shoulder imbalance (RSH 25.3 mm), a 6° DWA, and a high postoperative PTC/MTC ratio (2.4).

FIG. 3. Left: Preoperative radiograph of a 12-year-old girl showing well-balanced shoulders with a 37° PTC and 48° MTC. Right: Postoperative radiograph 5 years after surgery showing shoulder imbalance (RSH 25.05 mm), a 17° PWA, and a high postoperative PTC/MTC ratio (5.8).

FIG. 4. Left: Preoperative radiograph of a 15-year-old girl showing well-balanced shoulders with a 37° PTC and 49° MTC. Right: Postoperative radiograph 2 years after surgery revealing shoulder imbalance (RSH 25.4 mm) and a distal adding-on phenomenon (arrow).

FIG. 5. **Left:** Preoperative radiograph of a 17-year-old boy showing well-balanced shoulders with a 63° PTC and 61° MTC. **Right:** Postoperative radiograph 3 years after surgery showing balanced shoulders (RSH -6.0 mm), a 0° PWA, a 0° DWA, and a low postoperative PTC/MTC ratio (1.5).

in this regard, because in another study,⁵ T-1 tilt was considered to be an important factor for selecting the proximal fusion level.

A preoperative clavicle chest cage angle difference (CCAD) was suggested recently as a new parameter for predicting PSI.¹⁹ However, we did not find any relationship between the preoperative CCAD and PSI in our study. Therefore, further validation of this issue is required.

There are several critical considerations that need to be addressed in relation to PSI. First, RSH is not a clinical indicator of shoulder imbalance. Moreover, clinical shoulder imbalance does not correlate with radiographic shoulder imbalance. Accordingly, the concept of “cosmetic shoulder balance” has been suggested.¹⁵ Second, it is not clear how shoulder imbalance can be measured accurately, but several studies have reported the effectiveness of various methods.^{4,14,20} The clavicular angle and RSH are considered more reliable parameters according to a previous report.⁴ Third, the definition of PSI has not been clearly established. In the case of RSH, 10 and 20 mm were used as cutoff values in a number of studies.^{4,13} We used variable cutoff values of 20, 15, and 10 mm for sensitivity analysis. Fourth, the proximal fusion level for double thoracic idiopathic scoliosis has also been the subject of debate. Because of these complex considerations, interpreting our results is not completely straightforward.

This study had several notable limitations. First, our

results failed to reveal a meaningful association between preoperative parameters and PSI. Thus, we could not determine which radiographic parameters are predictive of PSI. Only associations between PSI and postoperative factors were evident in our findings. Thus, our results do not suggest any methods that could prevent PSI. Second, the number of patients in our PSI(+) group who met the criterion of a 20-mm RSH was relatively small, and therefore, a study with a larger sample size is needed to validate our results. Third, the average follow-up period (40 months) in our patient cohort was somewhat insufficient to determine the presence of the adding-on phenomenon or decompensation. A longer follow-up duration is needed to reveal more clearly the relationship between PSI and these factors. Fourth, a lack of clinical analysis, such as analysis using the Scoliosis Research Society-22 (SRS-22) score, was also a limitation in that radiographic shoulder imbalance is different from clinical shoulder imbalance.

The above-mentioned limitations notwithstanding, however, we reveal here for the first time that PWA correlates with PSI, and our data support and refute previously suggested findings. We believe that this correlation, which was derived from both sensitivity and multivariate logistic regression analyses, is relatively reliable. Thus, the results of our study provide a meaningful basis for further evaluation of the relationship between PTC correction and PSI in patients with AIS and a double thoracic curve.

Conclusions

PSI is correlated with a higher Risser grade, a larger postoperative PWA, and a higher postoperative PTC/MTC ratio in patients with AIS and a double thoracic curve. In addition, the presence of a distal adding-on phenomenon shows a correlation trend with an increasing PSI, although it was not found in our analysis to be statistically significant. However, no preoperative factor except for Risser grade affected the development of PSI. On the basis of these findings, more specific strategies might be required to prevent proximal wedging, unbalanced PTC/MTC correction, and the adding-on phenomenon. However, additional studies are required to reveal risk factors for the development of PSI.

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Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: Cho, CS Lee. Acquisition of data: Lim. Analysis and interpretation of data: Cho, Hwang, Lim. Drafting the article: Cho. Critically revising the article: Cho. Reviewed submitted version of manuscript: CS Lee, Lim, DH Lee. Approved the final version of the manuscript on behalf of all authors: Cho. Statistical analysis: Hwang, Lim. Administrative/technical/material support: CS Lee, Hwang, DH Lee. Study supervision: CS Lee, DH Lee.

Correspondence

Jae Hwan Cho, Department of Orthopedic Surgery, Asan Medical Center, University of Ulsan College of Medicine, 388-1 Pungnap-2-dong, SongPa-gu, Seoul, South Korea. email: doctork78@hanmail.net.