Factors for the acquisition of 10° angular change at the lumbar spine through posterior column osteotomy in adult spinal deformity surgery

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OBJECTIVE Posterior column osteotomy (PCO) has been known to provide an angular change (AC) of approximately 10° in sagittal plane deformity. However, whether PCO can actually obtain an AC of ≥ 10° depending on the particular level in the lumbar spine and which factors can effect a gain of ≥ 10° AC after PCO remain to be elucidated. The aim of this study was to identify the factors that effect a gain of ≥ 10° AC through PCO by comparing radiographic measurements between an AC group and a control group before and after adult spinal deformity (ASD) surgery.

METHODS Forty consecutive patients who underwent multilevel PCOs for ASD at a single institution between 2012 and 2016 were included in this study. PCO was performed in 142 disc space levels in the lumbar spine. The authors defined the disc space level that obtained ≥ 10° AC in the sagittal plane by PCO as the AC group and the remaining patients as controls. The modified Pfirrmann grade, surgical level, implementation of the transforaminal lumbar interbody fusion (TLIF), and radiographic measurements were compared between the groups.

RESULTS There were 67 levels in the AC group and 75 in the control group. Multivariate analysis identified the surgical level at L4–5 (OR 3.802, 95% CI 1.127–12.827, $p = 0.031$), performing TLIF with PCO (OR 3.303, 95% CI 1.258–8.674, $p = 0.015$), and a preoperative kyphotic disc space angle (OR 1.397, 95% CI 1.231–1.585, $p < 0.001$) as the factors that significantly effected ≥ 10° AC in the sagittal plane after PCO.

CONCLUSIONS In ASD surgery, PCO cannot always achieve ≥ 10° AC in the sagittal plane. The factors that effected ≥ 10° AC in PCO for ASD were surgical level at L4–5, performing TLIF with PCO, and the preoperative kyphotic disc space angle.

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KEYWORDS posterior column osteotomy; angular change; adult spinal deformity; lumbar spine

THE Smith-Petersen osteotomy was first reported in 1945 for an ankylosed and kyphotic spinal deformity due to rheumatic conditions.²³ The Ponte osteotomy was first described in 1984 for Scheuermann's kyphosis.^{7,21} In these procedures, the posterior elements are removed, except for the pedicles, to increase spinal column flexibility in the mobile segment and then shorten the posterior column by compression. As the 2 osteotomies are similar, they are also referred to as posterior column osteotomies (PCOs).^{1,8,16,18,20}

In terms of sagittal deformity correction, about 10° of

correction at each level can be gained with PCO. Geck et al.⁷ reported that the average correction across the apex was 9.3° per osteotomy in Scheuermann's kyphosis surgery with Ponte osteotomy. Cho et al.⁴ found that the mean correction with > 3 Smith-Petersen osteotomies was 33.0° ± 9.2°. However, they did not present precise information, including the location of the osteotomy, the change in disc space angle (DSA) at the location of the PCO, and the degree of disc degeneration. Furthermore, the patients in the previous studies were young, and their mobile segments might be flexible.

ABBREVIATIONS AC = angular change; ADH = anterior disc height; ASD = adult spinal deformity; BMD = bone mineral density; DSA = disc space angle; LL = lumbar lordosis; PCO = posterior column osteotomy; PDH = posterior disc height; PI = pelvic incidence; SVA = sagittal vertical axis; TK = thoracic kyphosis; TLIF = transforaminal lumbar interbody fusion.

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The factors effecting deformity correction, especially angle change, obtained by PCO in the treatment of adult spinal deformity (ASD) remain unknown. The purpose of this study was to identify the factors that effect a gain of $\geq 10^\circ$ angular change (AC) through PCO by comparing radiographic measurements between 2 groups, an AC group and a control group, before and after ASD surgery. We not only investigated the sagittal and pelvic parameters in ASD patients but also studied the radiographic parameters and radiological morphological type at each level where the PCO was performed.

Methods

Patient Population

This study was approved by the institutional review board at Seoul National University Bundang Hospital. A single institutional database was reviewed for all patients with spinal deformities who underwent posterior segmental spinal instrumentation by a single spine surgeon between 2012 and 2016. The inclusion criteria for our study were age at surgery of ≥ 50 years with a sagittal vertical axis (SVA) of > 5 cm, fusion with a minimum of 5 motion segments in the thoracolumbar and lumbar spine, and the performance of only multilevel PCOs in the lumbar spine. The exclusion criterion was the execution of a pedicle subtraction osteotomy or vertebral column resection.

Demographic and Surgical Data Collection

The patients' medical records were reviewed to identify demographic and surgical data, including age at surgery, sex, diagnosis, prior surgery, fused level, bone mineral density (BMD), length of follow-up, execution of PCO at each level, and transforaminal lumbar interbody fusion (TLIF) at the PCO level.

Radiographic Measurements, Imaging Assessments, and Establishment Method of Subgroups

Measurements were made on upright preoperative, immediately postoperative, and 1-month postoperative follow-up anteroposterior and lateral radiographs of the entire spine. On the lateral radiographs, SVA was measured as the distance from the C7 plumb line to the perpendicular line drawn from the superior posterior endplate of the S1 vertebral body (sagittal sacral vertical line). If the C7 plumb line fell behind the S1 vertebral body, the global sagittal balance was negative. If the C7 plumb line fell anterior to the sacrum, the sagittal balance was positive. If the C7 plumb line was on the sagittal sacral vertical line, the sagittal balance was zero. Lordotic angles were assigned negative values, whereas kyphotic angles were given positive values. Thoracic kyphosis (TK) was measured from the upper endplate of T5 to the lower endplate of T12, and lumbar lordosis (LL) was measured from the lower endplate of T12 to the upper endplate of S1. Pelvic incidence (PI) was the angle between the perpendicular to the sacral plate at its midpoint and the line connecting this point to the axis of the femoral head.^{3,22}

We measured the anterior disc height (ADH), the posterior disc height (PDH), and the DSA at each level where PCO was performed on preoperative and 1-month postop-

TABLE 1. Demographic data of the 40 patients who underwent PCO for ASD

Parameter	Value
Mean age at op, yrs	70.1 (6.2)
Sex, n (%)	
Female	37 (92.5%)
Male	3 (7.5%)
Diagnosis, n (%)	
Degenerative flat back	30 (75.0%)
Postop flat back	7 (17.5%)
Posttraumatic flat back	3 (7.5%)
Prior op, n (%)	9 (22.5%)
Mean no. of fused levels	8.4 (2.9)
Mean BMD T-score	-2.2 (1.1)
Mean follow-up duration, mos	14.7 (5.5)
Mean no. of PCO levels	3.6 (1.5)
No. of PCO levels ≥ 3 , n (%)	31 (77.5%)

Mean values are presented as the mean (SD).

erative whole-spine standing lateral radiographs (DSA_{Stand}). Moreover, preoperative DSAs on flexion (DSA_{Flexion}) and extension (DSA_{Extension}) at each PCO level were measured on preoperative lumbar spine lateral decubitus flexion and extension radiographs, respectively. T2-weighted turbo-spin sagittal images without fat suppression of the lumbar spine were obtained preoperatively. In addition, we graded disc degeneration using the modified Pfirrmann grading system at each PCO level.¹⁰ All PCO levels were divided into 2 groups. The levels at which the DSA_{Stand} changed $\geq 10^\circ$ after surgery were allocated to the AC group, and the remaining levels were classified as the control group. All radiographic measurements and radiological assessments were performed by a single spine surgeon.

Surgical Technique

The patients were placed prone on a Jackson table with the trunk supported at the upper thorax and thighs, leaving the abdomen free. We made an effort to restore the lordotic curve of the lumbar spine as much as possible through patient positioning. Subperiosteal dissection was performed meticulously to reach bony spine. Pedicle screw fixation was performed using the free-hand technique.^{12,19} PCO was performed as follows. First, the inferior facet of the superior vertebra was removed, and then the ligament flavum and superior facet of the inferior vertebra were resected for the opening of the epidural space. Third, the posterior osteotomy site was closed slowly with the aid of rods, pedicle screws, or a central hook-rod construct.¹³ TLIF using kidney-shaped crescent cages (Medtronic Sofamor Danek) was performed when interbody fusion was needed. Rods were placed on the pedicle screws, and a crosslink was used to connect the bilateral rods.

Statistical Analysis

The distributions of variables are presented as number with the percentage or mean with the standard deviation. Continuous variables were compared using the unpaired

TABLE 2. Radiographic outcomes

Parameter	Preop	Postop	p Value
Mean TK, °*	13.7 (9.1)	25.9 (9.3)	<0.001
Mean LL, °*	-7.0 (19.3)	-52.9 (11.4)	<0.001
Mean PT, °*	33.5 (12.5)	18.8 (6.5)	<0.001
Mean SVA, cm	166.4 (95.0)	23.0 (25.9)	<0.001
SVA >5 cm, n (%)	40 (100%)	0	
Mean PI-LL, °*	48.2 (19.8)	2.2 (6.6)	<0.001
PI-LL >10°, n (%)	40 (100%)	0	

Mean values are presented as the mean (SD).

* Positive values denote kyphosis, and negative values denote lordosis.

t-test for normally distributed data or the Mann-Whitney U-test for nonnormally distributed data. The paired t-test was used to assess for differences between preoperative and postoperative radiographic parameters. The chi-square or Fisher exact test was used for categorical variables. Multivariate logistic regression analysis was used to identify the factors that effect a gain of $\geq 10^\circ$ AC after PCO; $p < 0.05$ was considered statistically significant. All statistical analyses were performed using IBM SPSS (version 21.0, IBM Corp.).

Results

Patient Demographics and Radiographic Outcomes

The demographic data of all the included patients are presented in Table 1. Forty consecutive patients who had undergone spinal deformity surgery with multilevel PCOs at the lumbar spine and met the inclusion and exclusion criteria were identified. The mean patient age was 70.1 ± 6.2 years, and most (92.5%) were women. The diagnoses were degenerative flat back ($n = 30$), postoperative flat back ($n = 7$), and posttraumatic flat back ($n = 3$). Prior surgery was performed in 9 patients, and the mean number of fused levels was 8.4 ± 2.9 . The mean BMD T-score was -2.2 ± 1.1 , and the mean follow-up duration was 14.7 ± 5.5

months. The mean number of PCO levels was 3.6 ± 1.5 , and 31 patients had ≥ 3 levels of PCO.

Table 2 provides a summary of the radiographic outcomes and statistical comparisons in terms of preoperative and postoperative radiographic parameters. The mean PI was $55.2^\circ \pm 11.1^\circ$. The mean TK changed from $13.9^\circ \pm 9.1^\circ$ to $25.9^\circ \pm 9.3^\circ$ ($p < 0.001$), and the postoperative LL was restored to lordotic compared with the preoperative LL (preoperative LL $-7.0^\circ \pm 19.3^\circ$ vs postoperative LL $-52.9^\circ \pm 11.4^\circ$, $p < 0.001$). The mean SVA and PI-LL mismatch were significantly improved (preoperative SVA 16.64 ± 9.50 cm vs postoperative SVA 2.30 ± 2.59 cm, $p < 0.001$; preoperative PI-LL $48.2^\circ \pm 19.8^\circ$ vs postoperative PI-LL $2.2^\circ \pm 6.6^\circ$, $p < 0.001$), and the sagittal imbalance and PI-LL of $> 10^\circ$ were corrected in all patients after ASD surgery (preoperative SVA > 5 cm [$n = 40$] vs postoperative SVA > 5 cm [$n = 0$]; preoperative PI-LL mismatch $> 10^\circ$ [$n = 40$] vs postoperative PI-LL mismatch $> 10^\circ$ [$n = 0$]).

Radiological Assessments and Radiographic Outcomes According to Each PCO Level From T12–L1 to L5–S1

A total of 142 levels from T12–L1 to L5–S1 were treated using PCO. The numbers of levels where PCO was performed at each level were as follows: 7 levels at T12–L1, 20 levels at L1–2, 30 levels at L2–3, 28 levels at L3–4, 30 levels at L4–5, and 27 levels at L5–S1 (Table 3). Most PCO levels had a modified Pfirrmann grade of ≥ 5 (114/142, 80.2%). PCO was performed with TLIF at 56 (39.4%) levels, and most of the TLIFs were performed at L4–5 and L5–S1 (41/56, 73.2%). None of these levels had TLIF without PCO; PCO was performed without TLIF at 86 (60.6%) levels.

The radiographic results of all PCO levels are listed in Table 4. At all PCO levels from T12–L1 to L5–S1, the mean ADH and DSA_{Stand} increased, and the mean PDH decreased after surgery. The changes in the 3 parameters were statistically significant after multilevel PCOs were performed. A significant difference was found between preoperative DSA_{Extension} and DSA_{Flexion} at each PCO level. A change of $\geq 10^\circ$ in DSA_{Stand} (Δ DSA) at each PCO level

TABLE 3. Disc degeneration grade, and surgical method at each PCO level

Parameter	No. of Levels						Total (%) (n = 142)
	T12–L1 (n = 7)	L1–2 (n = 20)	L2–3 (n = 30)	L3–4 (n = 28)	L4–5 (n = 30)	L5–S1 (n = 27)	
Modified Pfirrmann grade							
1	0	0	0	0	0	0	0
2	1	1	0	0	0	0	2 (1.4)
3	1	2	3	2	1	3	12 (8.5)
4	2	5	1	3	3	0	14 (9.9)
5	2	7	7	5	2	6	29 (20.4)
6	0	1	10	8	8	10	37 (26.1)
7	0	1	1	4	10	5	21 (14.8)
8	1	3	8	6	6	3	27 (19.0)
No. of PCOs	7	20	30	28	30	27	142 (100)
No. of PCOs w/ TLIF	0	2	5	8	21	20	56 (39.4)
No. of PCOs w/o TLIF	7	18	25	20	9	7	86 (60.6)
No. of TLIFs w/o PCO	0	0	0	0	0	0	0

TABLE 4. Radiographic outcomes of each PCO level

Level	Preop Mean Value*					Postop Mean Value*					No. of Pts w/ ΔDSA ≥10° (n = 67)					
	ADH, cm	PDH, cm	DSA _{Stand} ^{o†}	DSA _{Flexion} ^{o†}	DSA _{Extension} ^{o†}	Difference Btwn DSA _{Extension} & DSA _{Flexion} ^{o†}	ADH, cm	PDH, cm	DSA _{Stand} ^{o†}	ΔADH, cm			p Value	ΔPDH, cm	p Value	ΔDSA, °†
T12-L1	6.5 (3.1)	6.3 (2.2)	-0.4 (4.2)	-3.0 (4.2)	-4.0 (2.9)	-0.1 (4.0)	9.5 (3.2)	5.3 (2.5)	-5.7 (3.7)	2.9 (2.8)	0.033	-1.0 (0.6)	0.004	-5.3 (3.5)	0.007	1 (1.5)
L1-2	8.2 (2.7)	6.7 (3.0)	-1.9 (5.0)	-0.5 (3.2)	-3.3 (3.9)	-2.8 (2.9)	12.1 (3.5)	4.7 (2.2)	-9.9 (5.3)	3.9 (3.9)	<0.001	-2.0 (3.2)	0.010	-8.0 (7.0)	<0.001	8 (11.9)
L2-3	6.4 (3.3)	6.2 (2.4)	-0.1 (4.9)	-0.7 (3.5)	-4.6 (5.1)	-4.0 (3.9)	12.3 (3.4)	5.2 (2.4)	-10.0 (4.1)	5.9 (4.4)	<0.001	-1.0 (3.3)	0.105	-9.9 (5.8)	<0.001	14 (20.9)
L3-4	8.0 (3.5)	7.4 (3.2)	0.5 (5.2)	0.1 (5.2)	3.9 (4.5)	-3.9 (5.1)	13.7 (3.4)	6.1 (2.3)	-9.4 (5.6)	5.7 (4.2)	<0.001	-1.3 (2.7)	0.018	-9.8 (6.1)	<0.001	11 (16.4)
L4-5	7.0 (3.4)	7.8 (3.0)	2.2 (6.1)	2.3 (4.8)	-4.7 (5.4)	-7.0 (3.9)	15.3 (3.4)	5.3 (2.2)	-12.4 (4.7)	8.3 (3.6)	<0.001	-2.5 (2.96)	<0.001	-14.6 (5.8)	<0.001	24 (35.8)
L5-S1	11.6 (4.2)	6.7 (3.0)	-6.6 (6.7)	-3.2 (4.9)	-8.4 (7.1)	-5.2 (4.7)	16.0 (3.4)	5.1 (2.3)	-14.9 (5.4)	4.4 (3.2)	<0.001	-1.6 (3.1)	0.011	-8.3 (5.5)	<0.001	9 (13.4)

Pts = patients.

* Mean values are presented as the mean (SD).

† Positive values denote kyphosis, and negative values denote lordosis.

TABLE 5. Disc degeneration grade, surgical level, surgical method, and preoperative radiologic measurements between AC and control groups

Parameter	AC Group (n = 67)	Control Group (n = 75)	p Value
Modified Pfirrmann grade, n			
1	0	0	
2	0	2	0.498
3	3	9	0.108
4	6	8	0.733
5	13	16	0.776
6	17	20	0.861
7	13	8	0.143
8	15	12	0.333
≤ 4	9	19	0.092
Surgical level, n			
T12–L1	1	6	0.120
L1–2	8	12	0.488
L2–3	14	16	0.949
L3–4	11	17	0.350
L4–5	24	6	<0.001
L5–S1	9	18	0.109
No. of PCO w/ TLIF	35	21	0.003
No. of PCO w/o TLIF	32	54	0.003
Mean preop ADH, cm	6.7 (3.2)	9.2 (4.1)	<0.001
Mean preop PDH, cm	7.6 (3.0)	6.3 (2.7)	0.007
Mean preop DSA _{Stand} , °*	2.7 (5.0)	-4.3 (5.4)	<0.001
Mean preop DSA _{Flexion} , °*	1.1 (5.2)	-1.9 (3.8)	<0.001
Mean preop DSA _{Extension} , °*	-4.0 (5.2)	-5.9 (5.5)	0.045
Mean preop DSA _{Extension} - mean preop DSA _{Flexion} , °*	-5.1 (4.7)	-4.1 (4.2)	0.150

Mean values are presented as the mean (SD). Boldface type indicates statistical significance.

* Positive values denote kyphosis, and negative values denote lordosis.

was acquired postoperatively for 67 segments. The numbers of levels where a Δ DSA of $\geq 10^\circ$ was gained were as follows: 1 level (1.5%) at T12–L1, 8 levels (11.9%) at L1–2, 14 levels (20.9%) at L2–3, 11 levels (16.4%) at L3–4, 24 levels (35.8%) at L4–5, and 9 levels (13.4%) at L5–S1. The location where a Δ DSA of $\geq 10^\circ$ frequently occurred was at the L4–5 level.

Comparative Analysis Between the AC and Control Groups

There were 67 (47.2%) patients in the AC group and 75 (52.8%) in the control group (Table 5). No statistically significant differences according to the modified Pfirrmann grade and modified Pfirrmann grade of ≤ 4 were found between the 2 groups. The surgical level at L4–5 was more common in the AC group than in the control group (24 vs 6, $p < 0.001$), and the other levels were not significantly different between the groups. There were 35 PCOs with TLIF in the AC group and 21 in the control group ($p =$

TABLE 6. Multivariate logistic regression analysis to determine the factors of the change of $DSA \geq 10^\circ$ after PCO for the treatment of ASD

Explanatory Variable	Univariate Analysis	Multivariate Analysis	OR (95% CI)
Level of PCO at L4–5	<0.001	0.031	3.802 (1.127–12.827)
PCO w/ TLIF	0.003	0.015	3.303 (1.258–8.674)
Preop ADH	<0.001	0.484	NS
Preop PDH	0.007	0.339	NS
Preop DSA_{Stand}	<0.001	<0.001	1.397 (1.231–1.585)
Preop $DSA_{Flexion}$	<0.001	0.666	NS
Preop $DSA_{Extension}$	0.045	0.943	NS

NS = not significant.

Boldface type indicates statistical significance.

0.003), giving 32 PCOs without TLIF in the AC group and 54 in the control group ($p = 0.003$). The preoperative ADH in the AC group was shorter than that in the control group. The preoperative PDH in the AC group was longer than that in the control group (preoperative ADH: 6.7 ± 3.2 mm vs 9.2 ± 4.1 mm, $p < 0.001$; preoperative PDH: 7.6 ± 3.0 mm vs 6.3 ± 2.7 mm, $p = 0.007$). The mean preopera-

tive DSA_{Stand} of the AC group was a kyphotic curve, and the mean preoperative DSA_{Stand} of the control group was a lordotic curve (preoperative DSA_{Stand} : AC group, $2.7^\circ \pm 5.0^\circ$ vs control group, $-4.3^\circ \pm 5.4^\circ$, $p < 0.001$). The preoperative $DSA_{Flexion}$ and preoperative $DSA_{Extension}$ for the control group were more lordotic than those for the AC group (preoperative $DSA_{Flexion}$: AC group, $1.1^\circ \pm 5.2^\circ$ vs control group, $-1.9^\circ \pm 3.8^\circ$, $p < 0.001$; preoperative $DSA_{Extension}$: AC group, $-4.0^\circ \pm 5.2^\circ$ vs control group, $-5.9^\circ \pm 5.5^\circ$, $p = 0.045$). No statistically significant difference in preoperative $DSA_{Extension} - \text{preoperative } DSA_{Flexion}$ was found between the 2 groups.

In multivariate logistic regression of significant factors in the univariate analysis, the level of PCO at L4–5, execution of PCO with TLIF, and preoperative DSA_{Stand} were the factors that contributed to a $\Delta DSA \geq 10^\circ$ after ASD surgery with multilevel PCOs (level of PCO at L4–5: OR 3.802, 95% CI 1.127–12.827, $p = 0.031$; execution of PCO with TLIF: OR 3.303, 95% CI 1.258–8.674, $p = 0.015$; preoperative DSA_{Stand} : OR 1.397, 95% CI 1.231–1.585, $p < 0.001$; Table 6).

Figure 1 shows a representative case in this study in which the surgical level of PCO at L4–5, execution of PCO with TLIF, and the preoperative kyphotic DSA_{Stand} were important for a gain in ΔDSA of $\geq 10^\circ$ after ASD surgery with multilevel PCOs.

FIG. 1. Lateral radiographs obtained in a 70-year-old woman with a degenerative flat back who underwent posterior spinal fusion from T9 to the pelvis using multilevel PCOs with TLIF at L3–4 and L4–5 for deformity correction. The preoperative values were as follows: SVA = 234.8 mm, LL = -1.7° , PI-LL = 67.5° , and DSA_{Stand} at L4–5 = 17.8° . The postoperative values were as follows: SVA = 23.3 mm, LL = -69.2° , PI-LL = 0.1° , and DSA_{Stand} at L4–5 = -20.9° . The ΔDSA at L4–5 was -38.7° . Negative values are assigned to lordotic angles, whereas positive values are assigned to kyphotic angles. Figure is available in color online only.

Discussion

Strategic Establishment of Multilevel PCOs

Three osteotomy methods have been used for the correction of sagittal spinal deformities, namely PCO, pedicle subtraction osteotomy, and vertebral column resection. PCO is well known to have a lower incidence of complications than the other osteotomy methods, including lower bleeding rates, shorter operative time, and lower risk of neurological disability.^{2,4–6,9,14,17} Therefore, if possible, PCO should be considered first in ASD surgery. A certain degree of angle correction was reported to have been obtained with multilevel PCOs in spinal deformity surgery.^{4,7} However, until now, there has been no definite strategy for multilevel PCOs in the treatment of ASD. Now, it is necessary to discuss the elements that should be focused on in ASD surgery with multilevel PCOs in order for the surgery to be a success. In this regard, this research may be important as it identifies the factors that effect a gain of $\geq 10^\circ$ AC through PCO.

Relationship Between Disc Degeneration Grade and AC

Modified Pfirrmann grades¹⁰ higher than 5 lack a water signal in the disc space, indicating a decrease in segmental mobility. In our study results, discs in most segments (114/142, 80.2%) were modified Pfirrmann grade ≥ 5 . Thus, we found no significant relationship between disc degeneration grade and AC in ASD surgery with multilevel PCOs. However, this relationship may be significant in a young patient.

Three Factors for a Gain of $\geq 10^\circ$ AC With Multilevel PCOs

Our results revealed that the surgical level at L4–5, execution of PCO with TLIF, and kyphotic DSA are important factors for AC in ASD treated by multilevel PCOs. First, much of the Δ DSA occurred at L4–5 compared with other levels after surgery (Table 4). Janik et al.¹⁵ made an ellipsoidal model of the lumbar spine and found that 65% of the LL was located between L4 and S1. Similar to their finding, our postoperative DSA_{Stand} at L4–5 and L5–S1 was larger than that at other levels. However, the Δ DSA was largest at L4–5, followed by L2–3 (rather than L5–S1). At the L5–S1 level, preoperative and postoperative DSA_{Stand} values were lordotic. Moreover, in a previous report, the shape of the disc space anatomy at L5–S1 was described as conical, with its posterior margin shorter than its anterior margin.¹¹ Therefore, it was more difficult to obtain a Δ DSA $\geq 10^\circ$ AC at L5–S1 than at L4–5. In summary, we attempted to maximize the L4–5 DSA with multilevel PCOs for ASD. Second, the disc degeneration grade of the levels included in this study was mostly grade 5 and higher, with a disc degeneration grade ≥ 6 in 59.9% of levels (85/142). A disc degeneration grade ≥ 6 indicates a decrease in disc height. When the height of the disc space was increased by placement of a cage before PCO was performed, the Δ DSA value increased. Inserting a cage in the disc space utilizes the principles of a lever and fulcrum so that the PCO closes the posterior margin as much as possible. Therefore, performing multilevel PCOs with TLIF was an important factor for a gain of $\geq 10^\circ$ AC. Finally, the kyphotic disc space could easily be changed

when the patient's position on the Jackson spine table was set for creating a lordotic curve of the lumbar spine, and through the execution of PCO, AC of the disc space was maximized. Therefore, the kyphotic DSA is a key factor for AC after multilevel PCOs for the treatment of ASD.

This study was performed retrospectively in patients who had good correction. The limitations of this study are that the number of patients is relatively small and the diagnosis of patients included in the study is heterogeneous. Moreover, the number of levels included in the study is also small. Although our study has a retrospective design, our findings are meaningful because we determined which part of surgery with multilevel PCOs for ASD should be focused on. Future studies are needed to investigate whether the number of PCO levels can be reduced by taking into consideration the 3 factors for the gain of AC during ASD surgery with multilevel PCOs.

Conclusions

In ASD surgery, PCOs cannot always achieve $\geq 10^\circ$ AC in the sagittal plane. The factors that can effect $\geq 10^\circ$ AC with PCOs for the treatment of ASD were surgical level at L4–5, performing PCO with TLIF, and the preoperative kyphotic DSA.

References

1. Bekmez S, Ozhan M, Olgun ZD, Suzer A, Ayvaz M, Demirkiran HG, et al: Pedicle subtraction osteotomy versus multiple posterior column osteotomies in severe and rigid neuromuscular scoliosis. *Spine (Phila Pa 1976)* **43**:E905–E910, 2018
2. Bridwell KH: Decision making regarding Smith-Petersen vs. pedicle subtraction osteotomy vs. vertebral column resection for spinal deformity. *Spine (Phila Pa 1976)* **31** (19 Suppl):S171–S178, 2006
3. Bridwell KH, Lewis SJ, Rinella A, Lenke LG, Baldus C, Blanke K: Pedicle subtraction osteotomy for the treatment of fixed sagittal imbalance. Surgical technique. *J Bone Joint Surg Am* **86-A** (Suppl 1):44–50, 2004
4. Cho KJ, Bridwell KH, Lenke LG, Berra A, Baldus C: Comparison of Smith-Petersen versus pedicle subtraction osteotomy for the correction of fixed sagittal imbalance. *Spine (Phila Pa 1976)* **30**:2030–2038, 2005
5. Dorward IG, Lenke LG: Osteotomies in the posterior-only treatment of complex adult spinal deformity: a comparative review. *Neurosurg Focus* **28**(3):E4, 2010
6. Enercan M, Ozturk C, Kahraman S, Sarier M, Hamzaoglu A, Alanay A: Osteotomies/spinal column resections in adult deformity. *Eur Spine J* **22** (Suppl 2):S254–S264, 2013
7. Geck MJ, Macagno A, Ponte A, Shufflebarger HL: The Ponte procedure: posterior only treatment of Scheuermann's kyphosis using segmental posterior shortening and pedicle screw instrumentation. *J Spinal Disord Tech* **20**:586–593, 2007
8. Ghobrial GM, Gjolaj JP: Multilevel posterior column osteotomies for sagittal plane correction in the management of adult degenerative scoliosis. *Spine J* **17** Suppl:S166–S167, 2017
9. Gill JB, Levin A, Burd T, Longley M: Corrective osteotomies in spine surgery. *J Bone Joint Surg Am* **90**:2509–2520, 2008
10. Griffith JF, Wang YXJ, Antonio GE, Choi KC, Yu A, Ahuja AT, et al: Modified Pfirrmann grading system for lumbar intervertebral disc degeneration. *Spine (Phila Pa 1976)* **32**:E708–E712, 2007

11. Han SH, Hyun SJ, Jahng TA, Kim KJ: A comparative radiographic analysis of fusion rate between L4–5 and L5–S1 in a single level posterior lumbar interbody fusion. **Korean J Spine** **12**:60–67, 2015
12. Hyun SJ, Kim YJ, Cheh G, Yoon SH, Rhim SC: Free hand pedicle screw placement in the thoracic spine without any radiographic guidance: technical note, a cadaveric study. **J Korean Neurosurg Soc** **51**:66–70, 2012
13. Hyun SJ, Lenke LG, Kim YC, Koester LA, Blanke KM: Long-term radiographic outcomes of a central hook-rod construct for osteotomy closure: minimum 5-year follow-up. **Spine (Phila Pa 1976)** **40**:E428–E432, 2015
14. Hyun SJ, Rhim SC: Clinical outcomes and complications after pedicle subtraction osteotomy for fixed sagittal imbalance patients: a long-term follow-up data. **J Korean Neurosurg Soc** **47**:95–101, 2010
15. Janik TJ, Harrison DD, Cailliet R, Troyanovich SJ, Harrison DE: Can the sagittal lumbar curvature be closely approximated by an ellipse? **J Orthop Res** **16**:766–770, 1998
16. Lewis SJ, Keshen SG, Kato S, Gazendam AM: Posterior versus three-column osteotomy for late correction of residual coronal deformity in patients with previous fusions for idiopathic scoliosis. **Spine Deform** **5**:189–196, 2017
17. Macagno AE, O'Brien MF: Thoracic and thoracolumbar kyphosis in adults. **Spine (Phila Pa 1976)** **31** (19 Suppl):S161–S170, 2006
18. Omid-Kashani F, Hasankhani EG, Ebrahimzadeh MH, Kachooei AR, Heidari H: Posterior surgery alone in the treatment of post-traumatic kyphosis by posterior column osteotomy, spondylodesis, instrumentation, and vertebroplasty. **Asian Spine J** **7**:260–266, 2013
19. Park JH, Hyun SJ, Kim KJ, Jahng TA: Free hand insertion technique of S2 sacral alar-iliac screws for spino-pelvic fixation: technical note, acadaveric study. **J Korean Neurosurg Soc** **58**:578–581, 2015
20. Pellisé F, Vila-Casademunt A: Posterior thoracic osteotomies. **Eur J Orthop Surg Traumatol** **24** (Suppl 1):S39–S48, 2014
21. Pérez-Gruoso FS, Cecchinato R, Berjano P: Ponte osteotomies in thoracic deformities. **Eur Spine J** **24** (Suppl 1):S38–S41, 2015
22. Ploumis A, Liu H, Mehdod AA, Transfeldt EE, Winter RB: A correlation of radiographic and functional measurements in adult degenerative scoliosis. **Spine (Phila Pa 1976)** **34**:1581–1584, 2009
23. Smith-Petersen MN, Larson CB, Aufranc OE: Osteotomy of the spine for correction of flexion deformity in rheumatoid arthritis. **J Bone Joint Surg** **27**:1–11, 1945

Disclosures

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: Hyun, Han. Acquisition of data: Hyun, Han, KJ Kim, HJ Kim. Analysis and interpretation of data: Hyun, Han, Jahng, HJ Kim. Drafting the article: Han. Critically revising the article: Hyun, Han, HJ Kim. Reviewed submitted version of manuscript: Han, KJ Kim, Jahng. Approved the final version of the manuscript on behalf of all authors: Hyun. Statistical analysis: Han. Administrative/technical/material support: Hyun, Han, KJ Kim.

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