Comparison of perioperative complications following posterior column osteotomy versus posterior-based 3-column osteotomy for correction of rigid cervicothoracic deformity: a single-surgeon series of 95 consecutive cases

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OBJECTIVE The correction of severe cervicothoracic sagittal deformities can be very challenging and can be associated with significant morbidity. Often, soft-tissue releases and osteotomies are warranted to achieve the desired correction. There is a paucity of studies that examine the difference in morbidity and complication profiles for Smith-Petersen osteotomy (SPO) versus 3-column osteotomy (3CO) for cervical deformity correction.

METHODS A retrospective comparison of complication profiles between posterior-based SPO (Ames grade 2 SPO) and 3CO (Ames grade 5 opening wedge osteotomy and Ames grade 6 closing wedge osteotomy) was performed by examining a single-surgeon experience from 2011 to 2018. Patients of interest were individuals who had a cervical sagittal vertical axis (cSVA) > 4 cm and/or cervical kyphosis > 20° and who underwent corrective surgery for cervical deformity. Multivariate analysis was utilized.

RESULTS A total of 95 patients were included: 49 who underwent 3CO and 46 who underwent SPO. Twelve of the SPO patients underwent an anterior release procedure. The patients' mean age was 63.2 years, and 60.0% of the patients were female. All preoperative radiographic parameters showed significant correction postoperatively: cSVA (6.2 cm vs 4.5 cm [preoperative vs postoperative values], $p < 0.001$), cervical lordosis (6.8° [kyphosis] vs -7.5°, $p < 0.001$), and T1 slope (40.9° and 35.2°, $p = 0.026$). The overall complication rate was 37.9%, and postoperative neurological deficits were seen in 16.8% of patients. The surgical and medical complication rates were 17.9% and 23.2%, respectively. Overall, complication rates were higher in patients who underwent 3CO compared to those who underwent SPO, but this was not statistically significant (total complication rate 42.9% vs 32.6%, $p = 0.304$; surgical complication rate 18.4% vs 10.9%, $p = 0.303$; and new neurological deficit rate 20.4% vs 13.0%, $p = 0.338$). Medical complication rates were similar between the two groups (22.4% [3CO] vs 23.9% [SPO], $p = 0.866$). Independent risk factors for surgical complications included male sex (OR 10.88, $p = 0.014$), cSVA > 8 cm (OR 10.36, $p = 0.037$), and kyphosis > 20° (OR 9.48, $p = 0.005$). Combined anterior-posterior surgery was independently associated with higher odds of medical complications (OR 10.30, $p = 0.011$), and preoperative kyphosis > 20° was an independent risk factor for neurological deficits (OR 2.08, $p = 0.011$).

CONCLUSIONS There was no significant difference in complication rates between 3CO and SPO for cervicothoracic deformity correction, but absolute surgical and neurological complication rates for 3CO were higher. A preoperative cSVA > 8 cm was a risk factor for surgical complications, and kyphosis > 20° was a risk factor for both surgical and neurological complications. Additional studies are warranted on this topic.

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KEYWORDS cervical; complications; kyphosis; spinal deformity; three-column osteotomy

THE health impact of symptomatic adult cervical deformity (ACD) is substantial, negatively affecting all EQ-5D domains, with disability scores comparable to blindness, emphysema, renal failure, and stroke.¹ Severe cervical kyphotic deformities can result in dysphagia, difficulty maintaining horizontal gaze, gait impairment, and compensatory axial neck and interscapular pain.² In fact,

in severe cases, cervical kyphosis and sagittal imbalance account for many instances of myelopathy, even in the absence of central stenosis.^{3–6} Abnormal cervical sagittal vertical axis (cSVA) has been identified as an important parameter. cSVA is positively correlated with neck disability scores and negatively with SF-36 physical component scores; in particular, a cSVA > 4.0 cm is correlated with the

ABBREVIATIONS ACD = adult cervical deformity; CL = cervical lordosis; cSVA = cervical sagittal vertical axis; PSO = pedicle subtraction osteotomy; SPO = Smith-Petersen osteotomy; 3CO = 3-column osteotomy.

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greatest disability.⁷ Fortunately, patients who undergo surgical correction of their cervical deformity gain significant clinical benefits⁸ and improvement in myelopathy scores (Nurick score and modified Japanese Orthopaedic Association score).⁹

The correction of cervicothoracic deformities is formidable and technically challenging, especially in cases with rigid and fused deformities that require release via spinal osteotomies. A number of different surgical strategies exist for cervical deformity correction, including anterior-only, posterior-only, and combined anterior-posterior approaches. However, the optimal surgical approach depends on a number of anatomical and deformity-specific considerations. Osteotomy types that can be performed in the cervicothoracic region include anterior column osteotomy, Smith-Petersen osteotomy (SPO), and posterior-based 3-column osteotomy (3CO) via pedicle subtraction osteotomy (PSO) or vertebral column resection. Cervical SPO has been shown to provide a mean angular correction of 10.1° and a mean translational correction of 1.8 cm per level. Conversely, a single-level PSO is able to provide 34.5° of angular correction on average, in addition to 2.5–4.5 cm of translational correction.¹⁰ Therefore, the use of multilevel SPO should be able to obtain equivalent correction to a single PSO.

Cervical and upper thoracic SPO and 3CO are powerful corrective techniques, but they have been associated with high morbidity and complication rates. Complication rates are as high as 43.6%, with mortality ranging from 1.3% to 6.7% and neurological complication rates ranging from 13.5% to 23.0%.^{9,11,12} Combined anterior-posterior approaches are associated with the highest rates of early complications.¹² Therefore, in select cases, there has been a progressive shift toward using posterior-only approaches to correct cervicothoracic deformities. There is a paucity of studies dedicated to examining the complication profile of posterior-based osteotomies in the correction of cervical deformity. Our study reviews the perioperative complications of patients who underwent either multilevel SPO or isolated 3CO for the correction of moderate to severe cervical deformity. A subgroup analysis was performed to compare perioperative complications between SPO and 3CO. In addition, using multivariate analysis, we sought to identify independent risk factors associated with the risk of postoperative complication.

Methods

This study was approved by the Committee of Human Research at the University of California, San Francisco.

Patients

A consecutive cohort of adult patients (18 years of age or older) with a diagnosis of cervical or cervicothoracic deformity who underwent a posterior-based osteotomy for deformity correction performed by the senior author (C.P.A.) was retrospectively identified from the years 2011 to 2018. Both multilevel SPO and 3CO were performed throughout the study period. Inclusion criteria were a cSVA of 4.0 cm or greater and/or cervical kyphosis > 20° treated with either SPO (Ames grade 2 SPO) or 3CO

(Ames grade 5 opening wedge osteotomy and Ames grade 6 closing wedge osteotomy).¹³ SPO includes complete resection of the superior and inferior facet joints typically from C3 to C7. This also involves removal of the ligamentum flavum, spinous processes, and lamina (partial in cases without central stenosis). The 3CO technique has been previously described by the senior author.⁸ Patients who had a diagnosis of a recent infection, acute trauma, and/or tumor were excluded. Indications for surgery were significant dysfunction, debilitating axial neck pain, and/or neurological deficits (radiculopathy and/or myelopathy). All patients underwent open deformity correction with long-segment instrumentation. The decision to utilize multilevel SPO or 3CO was dependent on a variety of patient- and deformity-specific factors. In general, multilevel SPO was utilized in patients who have rigid deformities primarily involving the subaxial cervical spine, have the majority of anterior and middle columns unfused (open disc spaces), and/or have low to normal T1 slopes. 3COs were reserved for cases of rigid fused cervical deformities with severe sagittal deformities and/or high T1 slope (which represent upper thoracic deformities resulting in cervical deformity).

Data Points

Demographics, baseline clinical variables, and surgical details were retrospectively reviewed and recorded; they included age, sex, body mass index, smoking status, preoperative neurological deficit (normal strength vs weakness), abnormal gait, osteotomy type (SPO vs 3CO), osteotomy level, number of levels fused, approach, use of decompression, and comorbidities (psychiatric disease, hypertension, diabetes, thyroid disease, gastrointestinal tract disease, cardiac disease, pulmonary disease, hyperlipidemia, hepatic disease, and renal disease). Radiographic parameters of interest included preoperative and postoperative cSVA, cervical lordosis (CL), T1 slope, and coronal Cobb angle. All measurements were made using standing upright 3-foot radiographs. The specific methodology used to measure these cervical parameters has been described in a review article by Scheer et al.⁷

The primary outcomes of interest were overall perioperative complications within the 30-day postoperative period; these were further stratified into neurological, surgical, and medical complications. A medical or surgical complication was defined as any unforeseen postoperative event that required additional medical and/or surgical intervention. A neurological complication was defined as new weakness on physical examination following cervical deformity correction. Sensory changes were not included.

Statistical Analysis

In order to assess the association between osteotomy grade and complications, descriptive statistics were used to summarize the cohort and univariate statistics were used to assess for associations between covariates and outcomes of interest. The chi-square test was used for comparison of categorical outcomes, and ANOVA was used for continuous outcomes. Multivariate analysis models were then employed to determine whether surgical parameters and changes in other covariates were indepen-

TABLE 1. Preoperative and postoperative cervical parameters following correction of rigid cervicothoracic deformity

Parameter	Preop Mean	SD	Postop Mean	SD	p Value
Overall					
cSVA (cm)	6.2	1.7	4.5	1.7	<0.001
CL (°)	6.8	26.7	-7.5	15.1	<0.001
T1 slope (°)	40.9	20.8	35.2	12.9	0.026
Coronal Cobb angle (°)	6.7	11.0	2.2	4.1	<0.001
Low grade					
cSVA (cm)	5.5	1.6	4.3	1.9	<0.001
CL (°)	14.0	28.4	-5.9	12.6	<0.001
T1 slope (°)	31.5	16.3	33.7	13.4	0.483
Coronal Cobb angle (°)	7.4	12.6	2.5	4.6	0.015
High grade					
cSVA (cm)	6.8	1.5	4.7	1.6	<0.001
CL (°)	0.0	23.3	-9.1	17.1	0.030
T1 slope (°)	49.8	20.8	36.7	12.5	<0.001
Coronal Cobb angle (°)	5.9	9.2	1.9	3.6	0.007

dently associated with the outcomes of interests. Logistic regression models were used for categorical outcomes, and ANOVA models were used for continuous outcomes. From the univariate analysis, all covariates with a p value < 0.200 were included in the multivariate model. Osteotomy grade was adjusted for in all multivariate models. For other univariate subgroup analysis, the chi-square test was used for categorical outcomes and ANOVA was used for continuous outcomes. A p value < 0.05 was used as the threshold for statistical significance. All statistics were performed with the use of SAS version 9.4.

Results

A total of 95 patients were included in the study: 46 who underwent SPO and 49 who underwent 3CO. The patients' mean age was 63.2 years, and 60.0% of patients were female. In the overall cohort, 61.1% of the patients presented with preoperative weakness and 56.8% presented with gait abnormalities. Of the 49 patients who underwent 3CO, osteotomies were performed at C7 (16.3%), T1 (16.3%), T2 (20.4%), T3 (26.5%), and T4 (20.4%). Most patients (87.4%) underwent posterior-only osteotomy, with 12.6% of SPO patients undergoing a combined anterior-posterior release. Twelve or more levels were instrumented in 52.6% of patients, and 81.1% of the patients underwent decompression.

Mean preoperative cervical parameters were as follows: cSVA, 6.2 cm; CL, 6.8° (kyphosis); T1 slope, 40.9°; and coronal Cobb angle, 6.7° (Table 1). Overall, there was a significant change in all cervical parameters following deformity correction: cSVA, 4.5 cm ($p < 0.001$); CL, -7.5° ($p < 0.001$); T1 slope, 35.2° ($p = 0.026$); and coronal Cobb angle, 2.2° ($p < 0.001$). We further stratified preoperative and postoperative radiographic outcomes by osteotomy grade (Table 1). For both SPO and 3CO, there were significant changes in all cervical parameters follow-

TABLE 2. Extent of correction achieved based on severity of preoperative sagittal deformity

	No. of Patients	%	Postop Change	SD	p Value
Preop cSVA (cm)					<0.001
2–4	6	6.3	1.4	1.1	
4–6	40	42.1	1.2	1.0	
6–8	33	34.7	2.0	1.3	
>8	16	16.8	3.7	2.2	
Preop kyphosis (°)					<0.001
≤20	69	72.6	11.8	8.6	
>20	26	27.4	38.4	23.5	

ing deformity correction, except for T1 slope. Patients who underwent SPO did not have a significant change in T1 slope. The magnitude of angular and translational correction achieved based on cSVA and kyphosis severity was also tabulated (Table 2). There was a significant difference between the magnitude of correction when considering deformity severity. A greater preoperative cSVA was associated with greater translational correction ($p < 0.001$): 2–4 cm of cSVA (1.4-cm correction), 4–6 cm of cSVA (1.2-cm correction), 6–8 cm of cSVA (2.0-cm correction), and > 8 cm of cSVA (3.7-cm correction). In patients with preoperative kyphosis > 20°, we observed 38.4° of correction compared to 11.8° in patients with a smaller kyphotic deformity ($p < 0.001$) (Table 2).

Table 3 compares the demographics, characteristics, and surgical details between patients who underwent SPO and patients who underwent 3CO for cervical deformity correction. Demographics and comorbidities were similar between the groups. However, 3CO patients had significantly higher preoperative cSVA values (mean 6.8 vs 5.5 cm, $p < 0.001$) and T1 slope (mean 49.8° vs 31.5°, $p < 0.001$) compared to SPO patients. 3CO patients had a greater number of mean levels fused (mean 14.2 vs 10.9 levels, $p < 0.001$), and the rate of decompression was higher (mean 93.9% vs 67.4%, $p = 0.001$). SPO patients had significantly greater cervical kyphosis (mean -14.0° vs 0.0°, $p = 0.010$), and more SPO patients underwent anterior-posterior approaches (mean 21.7% vs 4.1%, $p = 0.010$).

In all 95 patients, the overall complication rate was 37.9% (Table 4). Neurological complications occurred in 16.8% of patients. Surgical and medical complications occurred in 17.9% and 23.2%, respectively. There were no significant differences in all complication types between SPO and 3CO patients. Complication rates for SPO were 32.6% overall, 13.0% neurological, 10.9% surgical, and 23.9% medical. The complication rates for 3CO were 42.9% overall, 20.4% neurological, 18.4% surgical, and 22.4% medical. When stratified by osteotomy level, there were significantly higher rates of neurological deficits at C7 and T1: C7 (37.5%), T1 (37.5%), T2 (20.0%), T3 (15.4%), T4 (0.0%) ($p = 0.023$). On univariate analysis, significant factors associated with neurological complications included sex ($p = 0.044$), preoperative weakness ($p = 0.034$), and kyphosis ($p = 0.005$). For surgical complica-

TABLE 3. Comparison of demographics, patient characteristics, and surgical details between patients who underwent either SPO or 3CO

	SPO	3CO	p Value
Age (yrs)	65.4	61.1	0.365
Male sex	34.8	44.9	0.315
BMI (kg/m ²)	27.0	28.6	0.236
Comorbidities (%)			
Psychiatric	26.1	44.9	0.056
Stroke	8.7	10.5	0.108
Hypertension	37.0	40.8	0.700
Diabetes	6.5	14.3	0.218
Thyroid	8.7	12.2	0.573
Gastrointestinal	26.1	34.7	0.363
Pulmonary	30.4	20.4	0.261
Cardiac	13.0	16.3	0.652
Hyperlipidemia	13.0	16.3	0.652
Hepatic	8.7	4.1	0.356
Renal	2.2	4.1	0.595
Preop weakness (%)	47.8	30.6	0.086
Abnormal gait (%)	56.5	30.6	0.011
Radiographic			
cSVA (cm)	5.5	6.8	<0.001
CL (°)	-14.0	0.0	0.010
T1 slope (°)	31.5	49.8	<0.001
Coronal Cobb angle (°)	7.4	5.9	0.512
Surgical			
Levels fused (mean no.)	10.9	14.2	<0.001
Combined anterior-posterior (%)	21.7	4.1	0.010
Laminectomy (%)	67.4	93.9	0.001

BMI = body mass index.

tions, the significant factors were sex ($p = 0.009$), kyphosis ($p = 0.007$), and cSVA ($p = 0.037$). Only approach type was associated with medical complications ($p = 0.018$).

On multivariate analysis, male sex (OR 10.88, 95% CI 1.62–73.00; $p = 0.014$), kyphosis $> 20^\circ$ (OR 9.48, 95% CI 1.97–45.68; $p = 0.005$), and cSVA > 8 cm (OR 10.36, 95% CI 1.15–93.45; $p = 0.037$) were independently associated with higher odds of surgical complications (Table 5). Patients with kyphosis $> 20^\circ$ also had significantly higher odds of experiencing neurological complications relative to patients with a smaller kyphotic curvature (OR 2.08, 95% CI 1.81–6.53; $p = 0.011$). A combined anterior-posterior approach was an independent factor associated with medical complications (OR 10.30, 95% CI 1.69–62.67; $p = 0.011$).

To investigate the relationship between the magnitude of correction and the presence of complications, we compared preoperative and postoperative cSVA and kyphosis values in patients who experienced complications versus those who experienced no complications (Table 6). Patients who had a neurological or medical complication underwent significantly greater kyphosis correction ($p = 0.041$ and $p = 0.028$, respectively) than patients without

those complications. Patients who experienced a surgical complication underwent significantly greater correction of cSVA ($p = 0.039$) than those who did not.

Illustrative Cases

Postlaminectomy Kyphosis: PSO

A 54-year-old woman who had previously undergone cervical decompression presented with difficult holding up her head up and was found to have a severe rigid cervical deformity (postlaminectomy kyphosis) (Fig. 1A and B). CT scanning demonstrated a focal kyphotic deformity in which the C6 and C7 vertebral bodies fused together (Fig. 1C). Preoperative cervical parameters were as follows: cSVA, 9.4 cm; CL, -12° (kyphosis); C2 slope, 40° ; and T1 slope, 32° . The patient underwent a C6–7 PSO and C2–T10 instrumented posterior spinal fusion (Fig. 1D and E). Her postoperative parameters were as follows: cSVA, 4.7 cm; CL, 10° ; C2 slope, 25° ; and T1, slope 34° .

Postlaminoplasty Kyphosis: Multiple-Level SPO

A 61-year-old woman with a history of cervical laminoplasty presented with chin-on-chest deformity (Fig. 2A and B). Her preoperative cervical parameters were as follows: cSVA, 7.7 cm; CL, -40° (kyphosis); C2 slope, 45° ; and T1 slope, 37° . She underwent a C3–7 SPO C2–T10 instrumented posterior spinal fusion (Fig. 2C and D). Her postoperative cervical parameters were as follows: cSVA, 5.6 cm; CL, 2° ; C2 slope, 25° ; and T1 slope, 34° .

Discussion

Severe cervical and cervicothoracic deformities are considered the most debilitating of all spinal deformities.¹ Patients experience low self-esteem, poor quality of life, debilitating pain, and progressive neurological decline.^{2–6} Radiographic parameters such as cSVA have been shown to be strongly correlated with significant functional disability based on health-related quality-of-life questionnaires, specifically when cSVA is > 4.0 cm.¹⁴ However, there are mixed results and findings as to whether regional CL correlates with clinical outcomes and postoperative pain.^{15,16} In fact, some studies have suggested that changes in regional CL do not correlate significantly with clinical outcomes.¹⁷ However, correction of ACD has been shown to provide significant benefits with regard to Neck Disability Index, neck pain visual analog scale scores, and SF-36 physical component summary scores.⁸

The first consideration in surgically managing patients with cervicothoracic deformity is to determine the primary driver of the cervical abnormality (isolated cervical vs combined cervical and cervicothoracic junction vs isolated upper thoracic).¹⁸ This determination will impact the decision of choosing osteotomy type and level. For example, patients with a high T1 slope and low C2 slope likely have an upper thoracic deformity and would benefit from an upper thoracic osteotomy for cervicothoracic deformity correction. The observed differences in preoperative cervical parameters between SPO (greater CL) and 3CO (greater cSVA and T1 slope) patients help demonstrate these concepts. Multilevel SPOs are most effective

TABLE 4. Relationship of demographics and operative variables with perioperative complications

	Overall		Complications			Neurological			Surgical			Medical		
	No.	%	No.	%	p Value	No.	%	p Value	No.	%	p Value	No.	%	p Value
Total	95		36	37.9		16	16.8		17	17.9		22	23.2	
Age (yrs)					0.355			0.226			0.576			0.174
<55	11	11.6	6	54.5		0	0.0		1	9.1		5	45.5	
55–70	63	66.3	24	38.1		13	20.6		11	17.5		13	20.6	
>70	21	22.1	6	28.6		3	14.3		2	9.5		4	19.0	
Sex					0.262			0.044			0.009			0.691
Female	57	60.0	19	33.3		6	10.5		4	7.0		14	24.6	
Male	38	40.0	17	44.7		10	26.3		10	26.3		8	21.1	
BM (kg/m ²)					0.355			0.106			0.206			0.071
<18.5	3	3.2	0	0.0		0	0.0		0	0.0		0	0.0	
18.5–25.0	27	28.4	13	48.1		1	3.7		1	3.7		11	40.7	
25.0–30	35	36.8	12	34.3		9	25.7		7	20.0		6	17.1	
>30	30	31.6	11	36.7		6	20.0		6	20.0		5	16.7	
Smoking status					0.582			0.438			0.745			0.702
Never	45	47.4	15	33.3		7	15.6		6	13.3		9	20.0	
Former	36	37.9	16	44.4		5	13.9		5	13.9		10	27.8	
Active	14	14.7	5	35.7		4	28.6		3	21.4		3	21.4	
Comorbidities														
Psychiatric					0.623			0.194			0.230			0.342
No	61	64.2	22	36.1		8	13.1		7	11.5		16	9.8	
Yes	34	35.8	14	41.2		8	23.5		7	20.6		6	17.6	
Stroke					0.679			0.620			0.959			0.868
No	81	85.3	30	37.0		13	16.0		12	14.8		19	23.5	
Yes	14	14.7	6	42.9		3	21.4		2	14.3		3	21.4	
Hypertension		0.0			0.679			0.489			0.788			0.777
No	58	61.1	23	39.7		11	19.0		9	15.5		14	24.1	
Yes	37	38.9	13	35.1		5	13.5		5	13.5		8	21.6	
Diabetes					0.404			0.778			0.788			0.588
No	85	89.5	31	36.5		14	16.5		12	14.1		19	22.4	
Yes	10	10.5	5	50.0		2	20.0		2	20.0		3	30.0	
Thyroid					0.885			0.240			0.150			0.297
No	85	89.5	32	37.6		13	15.3		11	12.9		21	24.7	
Yes	10	10.5	4	40.0		3	30.0		3	30.0		1	10.0	
Gastrointestinal					0.170			0.945			0.648			0.050
No	66	69.5	28	42.4		11	16.7		9	13.6		19	28.8	
Yes	29	30.5	8	27.6		5	17.2		5	17.2		3	10.3	
Pulmonary					0.963			0.062		9		0.330		0.755
No	71	74.7	27	38.0		9	12.7		5	7.0		17	23.9	
Yes	24	25.3	24	100.0		7	29.2			0.0		5	20.8	
Cardiac					0.856			0.782			0.959			0.755
No	81	85.3	31	38.3		14	17.3		12	14.8		18	22.2	
Yes	14	14.7	5	35.7		2	14.3		2	14.3		4	28.6	
Hyperlipidemia					0.312			0.620			0.444			0.394
No	81	85.3	29	35.8		13	16.0		11	13.6		20	24.7	
Yes	14	14.7	7	50.0		3	21.4		3	21.4		2	14.3	
Hepatic					0.812			0.991			0.890			0.697
No	89	93.7	34	38.2		15	16.9		13	14.6		21	23.6	
Yes	6	6.3	6	100.0		1	16.7		1	16.7		1	16.7	

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TABLE 4. Relationship of demographics and operative variables with perioperative complications

	Overall		Complications			Neurological			Surgical			Medical		
	No.	%	No.	%	p Value	No.	%	p Value	No.	%	p Value	No.	%	p Value
<i>Comorbidities (continued)</i>														
Renal					0.869			0.428			0.356			0.334
No	92	96.8	35	38.0		16	17.4		13	14.1		22	23.9	
Yes	3	3.2	1	33.3		0	0.0		1	33.3		0	0.0	
Preop weakness					0.381			0.034			0.358			0.200
No	58	61.1	24	41.4		6	10.3		7	12.1		16	27.6	
Yes	37	38.9	12	32.4		10	27.0		7	18.9		6	16.2	
Abnormal gait					0.381			0.545			0.980			0.804
No	54	56.8	20	37.0		8	14.8		8	14.8		12	22.2	
Yes	41	43.2	16	39.0		8	19.5		6	14.6		10	24.4	
Kyphosis (°)					0.381			0.005			0.007			0.991
≤20	69	72.6	24	34.8		7	10.1		6	8.7		16	23.2	
>20	26	27.4	12	46.2		9	34.6		8	30.8		6	23.1	
cSVA					0.095			0.099			0.037			0.642
2–4	6	6.3	3	50.0		1	16.7		1	16.7		2	33.3	
4–6	40	42.1	11	27.5		4	10.0		3	7.5		7	17.5	
6–8	33	34.7	12	36.4		6	18.2		4	12.1		8	24.2	
>8	16	16.8	10	62.5		5	31.3		6	37.5		5	31.3	
Osteotomy type					0.304			0.338			0.303			0.866
Low grade	46	48.4	15	32.6		6	13.0		5	10.9		11	23.9	
High grade	49	51.6	21	42.9		10	20.4		9	18.4		11	22.4	
Levels fused					0.385			0.751			0.831			0.096
<12	45	47.4	15	33.3		7	15.6		7	15.6		7	15.6	
≥12	50	52.6	21	42.0		9	18.0		7	14.0		15	30.0	
Approach					0.355			0.095			0.123			0.018
Posterior only	83	87.4	30	36.1		16	19.3		14	16.9		16	19.3	
Combined anterior-posterior	12	12.6	6	50.0		0	0.0		0	0.0		6	50.0	
Laminectomy					0.525			0.982			0.630			0.079
No	18	18.9	8	44.4		3	16.7		2	11.1		7	38.9	
Yes	77	81.1	28	36.4		13	16.9		12	15.6		15	19.5	

for patients with rigid subaxial cervical deformities resulting in cervical kyphosis, and 3COs are used in patients not only with rigid, fused deformities but also with severe sagittal imbalance (head translation) and high T1 slope. Based on prior studies, the ideal postoperative cSVA is < 4.0 cm.¹⁴ The goal for CL can be predicted by utilizing cervical mismatch measurements ($CL = T1 \text{ slope} - 16.5^\circ \pm 2^\circ$).¹⁹ Surgical correction of moderate to severe cervical deformities often requires soft-tissue release and osteotomies. An anterior-only, posterior-only, or combined anterior-posterior approach can be utilized.

Posterior-based cervical osteotomies and releases are useful options for the correction of severe sagittal deformities involving the cervical spine. Traditionally, for rigid cervical kyphotic deformities, SPO is used; this was often supplemented by a controlled wedge fracture (particularly at C7) or concurrent anterior release to restore

sagittal balance.^{20–22} A single-level SPO can offer 10.1° of angular and 1.8 cm of translational correction on average. When supplemented with an anterior release, averages of 27.8° of angular and 2.6 cm of translational correction can be achieved.¹⁰ The cervical SPO is thought to offer greater controlled closure and stronger biomechanical stability, while avoiding the anterior open wedge defects found in the traditional cervical PSO.^{23,24} However, given the smaller magnitude of correction possible with SPO, there is a growing interest in utilizing 3CO via PSO for cervicothoracic deformity correction.^{8,25–27} Cervical PSO is a technique that can offer correction for fixed coronal deformities as well.²⁸ Recent efforts have demonstrated a push toward performing PSO in the cervicothoracic junction, mainly at T1, T2, or T3.²⁵ The reasons for this are multifold: the canal diameter is larger in the lower cervical and upper thoracic spine, iatrogenic injury below the

TABLE 5. Independent risk factors for specific perioperative complications following correction of rigid cervicothoracic deformity

Independent Risk Factor	OR	95% CI (Min)	95% CI (Max)	p Value
Surgical				
Sex				
Female	Ref	Ref	Ref	Ref
Male	10.88	1.62	73.00	0.014
Kyphosis (°)				
≤20	Ref	Ref	Ref	Ref
>20	9.48	1.97	45.68	0.005
cSVA				
2–4	Ref	Ref	Ref	Ref
4–6	0.79	0.05	12.49	0.864
6–8	3.71	0.23	60.68	0.359
>8	10.36	1.15	93.45	0.037
Neurological				
Kyphosis				
≤20	Ref	Ref	Ref	Ref
>20	2.08	1.81	6.53	0.011
Medical				
Approach				
Posterior only	Ref	Ref	Ref	Ref
Combined anterior-posterior	10.30	1.69	62.67	0.011

Ref = reference.

cervical levels can spare the upper extremities, and lower cervical or upper thoracic PSO allows for avoidance of the vertebral arteries, which enter the transverse foramen at C6.^{29–31} Lower cervical and upper thoracic PSO can offer cSVA correction of 2.2 to 4.5 cm, cervical sagittal Cobb correction of 10.1° to 34.5°, and average chin-brow vertical angle correction of 36.7°.^{8,10,25} According to our findings, multilevel SPO and 3CO are able to provide similar corrective abilities.

Multilevel SPOs and PSOs are clearly extremely powerful techniques for the correction of fixed cervical sagittal deformities but have been associated with high complication rates. There are no large studies comparing the complication profiles between multilevel SPO and 3CO for cervical and cervicothoracic deformity correction. In our study, comparison of multilevel SPO and 3CO did not demonstrate a statistically significant difference in radiological correction; however, 3CO had higher absolute rates of overall, neurological, and surgical complications by 10.3%, 7.4%, and 7.5%, respectively. These differences in complication rates are clinically significant and should be considered in surgical planning. The overall complication rate of 37.9% observed in our cohort is similar to prior reports. Smith and colleagues performed a prospective multicenter study of 78 patients undergoing correction of ACD and found that 43.6% of patients experienced at least one complication.²⁵ In that study, the most common complications were dysphagia (11.5%), wound infections (6.4%), C5 nerve palsy (6.4%), and respiratory failure (5.1%). Complications

TABLE 6. Relationship between the severity of sagittal deformity and complications

Complication	Kyphosis Correction			cSVA Correction		
	Mean	SD	p Value	Mean	SD	p Value
Complication			0.041			0.213
No	16.1	14.4		1.8	1.5	
Yes	24.1	23.1		2.2	1.8	
Surgical			0.345			0.039
No	18.3	19.0		1.8	1.6	
Yes	23.4	15.1		2.5	1.8	
Medical			0.028			0.464
No	16.8	14.6		1.9	1.6	
Yes	26.6	26.9		2.1	1.7	

were highest following combined anterior-posterior approaches (79.3%).²⁵ In a comprehensive literature review of 14 studies and 399 patients, mortality rates ranged from 3.1% to 6.7%, and medical complication rates ranged from 3.1% to 44.4% following surgery for symptomatic cervical and cervicothoracic kyphosis.⁹

The most devastating complications that can occur during cervical deformity surgery result from injury to the vertebral artery, spinal cord, or nerve roots. Fortunately, vertebral artery injuries are extremely rare. The neurological complication rate in our study was 16.8%, which was within the ranges of prior reports. Reported rates of postoperative neurological deficit following cervical deformity correction range from 12.8% to 23.4%.^{11,12,29} In our study, 3CO patients had higher absolute rates of neurological complications than SPO. The observed 3CO neurological deficit rate of 20.4% is similar to those of prior published studies. This may reflect the greater technical difficulty associated with a 3CO and/or larger extent of correction achieved at a single focal point (which may put patients at higher risk of dural buckling and nerve root impingement). Samudrala et al. reviewed their experience with 8 patients who underwent PSO for cervicothoracic kyphosis; 3 patients (37.5%) had neurological deficits. Two patients had transient hand numbness and weakness, and 1 patient had right upper-extremity weakness requiring reoperation.³² This neurological deficit rate was similar to that in the study published by Tokala et al. in which the authors reported C8 radiculopathy in 3 (37.5%) of 8 patients following C7 PSO for cervicothoracic kyphosis. The C8 radiculopathies were transient and resolved within 4 weeks.³³ In a study of 23 patients undergoing 3CO for cervicothoracic deformities, Smith et al. reported a postoperative neurological deficit in 17.4% of patients.²⁵ Based on our experience as well as prior published studies, it is clear that there is a real risk of neurological complications when performing cervical deformity correction. Neuromonitoring modalities (MEP, SSEP, and EMG) are essential in minimizing injury to neural elements, but their performance measures have not been thoroughly studied for cervical deformity correction via SPO or 3CO.

An important component to planning a 3CO for cervical deformity correction is to consider the level in which

FIG. 1. Preoperative and postoperative images of a patient with severe cervicothoracic kyphosis following cervical decompression who underwent C6–7 PSO and instrumented C2–T10 posterior spinal fusion. Anterior-posterior and lateral scoliosis radiographs show severe cervicothoracic kyphosis: cSVA, 9.4 cm; CL, -12° (kyphosis); C2 slope, 40° ; and T1 slope, 32° (A and B). Sagittal CT scan showing fused C6 and C7 segment with a rigid, focal kyphotic deformity (C). As seen on scoliosis radiographs, significant correction of the patient's cervical deformity was achieved. Postoperative parameters were cSVA, 4.7 cm; CL, 10° ; C2 slope, 25° ; and T1 slope, 34° (D and E).

FIG. 2. Preoperative and postoperative scoliosis radiographs of a patient with severe cervical kyphosis who underwent deformity correction via C3–7 SPO and instrumented C2–T10 posterior spinal fusion. Prior cervical laminoplasty can be seen in her preoperative radiographs (A and B). The patient's preoperative cervical parameters were cSVA, 7.7 cm; CL, -40° (kyphosis); C2 slope, 45° ; and T1 slope, 37° . Her postoperative cervical parameters were cSVA, 5.6 cm; CL, 2° ; C2 slope, 25° ; and T1 slope, 34° (C and D).

it will be performed because this likely has a significant impact on neurological complication rates. As seen in this study, there were significantly lower neurological complication rates when 3CO was performed at more distal levels. This trend has been seen when comparing 3CO in the lower cervical region as opposed to the upper thoracic region, with lower cervical osteotomies associated with longer intensive care unit stay, hospital stay, and higher complications.²⁶ As such, the senior author has made a transition to shift 3CO to the most distal vertebral levels when possible (balancing the risk of neurological complications with the ability to achieve adequate deformity correction). This may have contributed to nonsignificant differences in the surgical and neurological complication rates between 3CO and SPO.

As we continue to learn more about the clinical benefits of cervical deformity correction, it is imperative that we mitigate and minimize perioperative complications. In patients who have undergone cervical deformity correction, one of the most important predictors of worse Neck Disability Index and modified Japanese Orthopaedic Association scores at the 1-year follow-up was the occurrence of a major complication following surgery.³⁴ Therefore, avoiding perioperative complications will in turn improve long-term outcomes for patients. According to the findings from our study, deformity severity seems to be an independent variable associated with risk for complications. Our study suggests that preoperative kyphosis $> 20^\circ$ and cSVA > 8 cm are both independent risk factors for surgical complications. Kyphosis $> 20^\circ$ was an independent risk factor for neurological complications as well. These findings are most likely because severe sagittal deformity requires greater corrective maneuvers. Therefore, preoperative counseling of patients regarding their increased risk of complication is important, and greater caution should be taken for such patients.

The main limitations of this study relate primarily to the retrospective nature of the data, relatively small cohort size, and heterogeneity of cervical deformity. Retrospective studies are at risk of inherent biases and unforeseen or unmeasurable confounders. We minimize heterogeneity between the two groups by studying a single-surgeon experience, but the best methodology of comparing two procedures would be to perform a multicenter prospective randomized trial. Severe cases of ACD are uncommon and make up a small fraction of a spine surgeon's practice, even for established deformity surgeons. Therefore, the number of study subjects is relatively small compared to other spine surgery studies. In this particular study, this limits the power of the analysis and constrains our ability to identify significant findings between smaller differences. An example includes the slightly higher neurological and surgical complication rates seen with 3CO compared to SPO, which were not significant on statistical analysis. Nonetheless, this is the largest single-center cohort study reported to date and it still has adequate power for multivariate analysis. It is also important to highlight that cervical deformity is a heterogeneous disease, and the surgical management varies based on numerous patients and deformity-specific factors. Patients who undergo SPO and 3CO likely have different types of cervical deformity, and this may limit the ability to directly compare complica-

tions and outcomes between those patients. At the same time, it is critical to understand the complication profile and differences when discussing surgical options with patients and deciding whether multilevel SPO or 3CO is the best strategy in cases when both osteotomies are suitable.

Conclusions

Posterior-based multilevel SPO and 3CO are powerful techniques for the correction of moderate to severe cervical sagittal deformity. Our findings suggest that excellent and equivalent correction can be achieved with either technique, with the exception that SPO does not change T1 slope and that the extent of correction is influenced by the severity of the cervical deformity. Complication rates were high, with approximately 40% of patients experiencing at least one complication. The neurological, surgical, and medical complication rates were 16.8%, 17.9%, and 23.2%, respectively. Patients who underwent 3CO had higher rates of neurological and surgical complications; when compared to larger cohorts, we would expect to see a statically significant difference. Therefore, larger cohort studies are needed to further validate these findings. Independent risk factors for surgical complications identified in our analysis included male sex, preoperative kyphosis $> 20^\circ$, and preoperative cSVA > 8 cm. Preoperative kyphosis $> 20^\circ$ was also a risk factor for neurological complications. Patients exhibiting these factors should be counseled preoperatively about their increased risk for complications. Unfortunately, these specific-risk factors are not modifiable. A combined anterior-posterior approach was an independent factor for medical complications. This suggests that when possible, a posterior-only approach may minimize medical-related complications. Additional studies are needed on this topic, especially multicenter prospective studies, in order to impact surgical decision-making for this population of patients.

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Conception and design: Lau, Ames. Acquisition of data: Lau. Analysis and interpretation of data: Lau, Deviren, Ames. Drafting the article: Lau. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Lau. Statistical analysis: Lau. Study supervision: Ames.

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