JNS SPINE

CLINICAL ARTICLE

J Neurosurg Spine 35:761–773, 2021

Global coronal decompensation and adult spinal deformity surgery: comparison of upper-thoracic versus lower-thoracic proximal fixation for long fusions

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OBJECTIVE Deterioration of global coronal alignment (GCA) may be associated with worse outcomes after adult spinal deformity (ASD) surgery. The impact of fusion length and upper instrumented vertebra (UIV) selection on patients with this complication is unclear. The authors' objective was to compare outcomes between long sacropelvic fusion with upper-thoracic (UT) UIV and those with lower-thoracic (LT) UIV in patients with worsening GCA ≥ 1 cm.

METHODS This was a retrospective analysis of a prospective multicenter database of consecutive ASD patients. Index operations involved instrumented fusion from sacropelvis to thoracic spine. Global coronal deterioration was defined as worsening GCA ≥ 1 cm from preoperation to 2-year follow-up.

RESULTS Of 875 potentially eligible patients, 560 (64%) had complete 2-year follow-up data, of which 144 (25.7%) demonstrated worse GCA at 2-year postoperative follow-up (35.4% of UT patients vs 64.6% of LT patients). At baseline, UT patients were younger (61.6 ± 9.9 vs 64.5 ± 8.6 years, p = 0.008), a greater percentage of UT patients had osteoporosis (35.3% vs 16.1%, p = 0.009), and UT patients had worse scoliosis (51.9° ± 22.5° vs 32.5° ± 16.3°, p < 0.001). Index operations were comparable, except UT patients had longer fusions (16.4 ± 0.9 vs 9.7 ± 1.2 levels, p < 0.001) and operative duration (8.6 ± 3.2 vs 7.6 ± 3.0 hours, p = 0.023). At 2-year follow-up, global coronal deterioration averaged 2.7 ± 1.4 cm (1.9 to 4.6 cm, p < 0.001), scoliosis improved (39.3° ± 20.8° to 18.0° ± 14.8°, p < 0.001), and sagittal spinopelvic alignment improved significantly in all patients. UT patients maintained smaller positive C7 sagittal vertical axis (2.7

ABBREVIATIONS ASD = adult spinal deformity; GCA = global coronal alignment; GCM = global coronal malalignment; HRQL = health-related quality of life; LSDI = Lumbar Stiffness Disability Index; LT = lower-thoracic; MCID = minimal clinically important difference; MCS = mental component summary; NRS = numerical rating scale; ODI = Oswestry Disability Index; PCS = physical component summary; PT = pelvic tilt; SRS-22r = Scoliosis Research Society–22r; SVA = sagittal vertical axis; TK = thoracic kyphosis; UT = upper-thoracic; UIV = upper instrumented vertebra.

SUBMITTED October 28, 2020. **ACCEPTED** February 15, 2021.
INCLUDE WHEN CITING Published online August 27, 2021; DOI: 10.3171/2021.2.SPINE201938.

± 5.7 vs 4.7 ± 5.7 cm, p = 0.014). Postoperative 2-year health-related quality of life (HRQL) significantly improved from baseline for all patients. HRQL comparisons demonstrated that UT patients had worse Scoliosis Research Society–22r (SRS-22r) Activity (3.2 ± 1.0 vs 3.6 ± 0.8, p = 0.040) and SRS-22r Satisfaction (3.9 ± 1.1 vs 4.3 ± 0.8, p = 0.021) scores. Also, fewer UT patients improved by ≥ 1 minimal clinically important difference in numerical rating scale scores for leg pain (41.3% vs 62.7%, p = 0.020). Comparable percentages of UT and LT patients had complications (208 total, including 53 reoperations, 77 major complications, and 78 minor complications), but the percentage of reoperated patients was higher among UT patients (35.3% vs 18.3%, p = 0.023). UT patients had higher reoperation rates of rod fracture (13.7% vs 2.2%, p = 0.006) and pseudarthrosis (7.8% vs 1.1%, p = 0.006) but not proximal junctional kyphosis (9.8% vs 8.6%, p = 0.810).

CONCLUSIONS In ASD patients with worse 2-year GCA after long sacropelvic fusion, UT UIV was associated with worse 2-year HRQL compared with LT UIV. This may suggest that residual global coronal malalignment is clinically less tolerated in ASD patients with longer fusion to the proximal thoracic spine. These results may inform operative planning and improve patient counseling.

https://thejns.org/doi/abs/10.3171/2021.2.SPINE201938

KEYWORDS adult spinal deformity; complications; coronal imbalance/malalignment; HRQL; health-related quality of life; outcomes; scoliosis surgery; upper instrumented vertebra; global coronal alignment

Postoperative global coronal malalignment (GCM) after adult spinal deformity (ASD) surgery is common, with some reports suggesting that up to 32% of patients experience this complication.[1–4] The postoperative occurrence of GCM may be an iatrogenic phenomenon in previously balanced patients or related to worsening baseline deformity.[1] Regardless of its etiology, recent studies have demonstrated that postoperative (or residual) GCM may be associated with worse outcomes.[2,3,5,6] Although potential risk factors of residual GCM have been identified (e.g., inadequate correction of lumbosacral fractional curve), currently there are limited studies focused on this operative complication.[2,4]

It is possible that postoperative GCM may be clinically less tolerated in ASD patients with longer fusion compared with those with shorter, limited fusion and more nonfused spine potentially available for reciprocal compensation. As such, focused investigation of this operative complication could provide results to better inform optimal selection of upper instrumented vertebra (UIV) when planning long fusion for patients with ASD. Currently, comparative ASD studies of upper-thoracic (UT) versus lower-thoracic (LT) UIV lack thorough assessment of global coronal alignment (GCA) and the potential negative clinical impact of postoperative global coronal deterioration.[7–12] Therefore, the objective of the present study was to first identify operatively treated ASD patients with worse GCA ≥ 1 cm at 2-year follow-up, and then to compare associated outcomes between UT and LT surgical groups. Our study hypothesis was that global coronal deterioration may be clinically less tolerated in patients who undergo UT fusion, and this may manifest as worse associated health-related quality of life (HRQL) outcomes compared with patients who undergo LT fusion.

Methods

Patient Population

This study was a retrospective review of a prospectively collected database of consecutive ASD patients who were enrolled at multiple IRB-approved sites across the United States. Database enrollment required patient age ≥ 18 years and at least one of the following radiographic measurements: scoliosis ≥ 20°, C7–S1 sagittal vertical axis (SVA) ≥ 5 cm, pelvic tilt (PT) ≥ 25°, and thoracic kyphosis (TK) ≥ 60°. Patients were excluded if they had active infection, malignancy, or diagnosis of scoliosis other than de novo degenerative or idiopathic. After provision of informed consent and database enrollment, patients were assigned to operative or nonoperative treatment arms on the basis of the initial management directed by the operating surgeon. The primary focus of this study was operatively treated patients with worse GCA ≥ 1 cm from preoperation to 2-year follow-up. Study inclusion required index operative treatment with posterior instrumented fusion (including operations performed with an anterior approach) from sacropelvis to thoracic spine. Study patients were analyzed on the basis of UIV location as follows: UT (T1–6) versus LT (T7–12). Figure 1 depicts representative preoperative and postoperative standing radiographs of UT and LT patients.

Data Collection and Radiographic Analysis

Baseline preoperative and 2-year follow-up postoperative data were collected for analysis, and demographic characteristics, index operations, radiographic measures, and HRQL outcome measures were included. Standardized assessments of HRQL included the Oswestry Disability Index (ODI),[13] Lumbar Stiffness Disability Index (LSDI),[11,12,14] SF-36 with scores for the physical component summary (PCS) and mental component summary (MCS),[15] and Scoliosis Research Society–22r (SRS-22r) questionnaire.[16,17] The SRS-22r instrument provides a total score and 5 subdomain scores for Activity, Pain, Appearance, Mental, and Satisfaction.[16,17] Back and leg pain were assessed using the numerical rating scale (NRS), with severity scores ranging from 0 (no pain) to 10 (unbearable pain). Values for minimal clinically important difference (MCID) have been established to provide clinical context when assessing HRQL.[18–21] In this study, the postoperative 2-year HRQL outcome measures were analyzed to determine the percentages of patients who achieved ≥ 1 MCID threshold of improvement.[18,19,22]

Assessment of complications was based on physical examination, imaging review, and standardized collection forms. On-site study coordinators assisted in record-

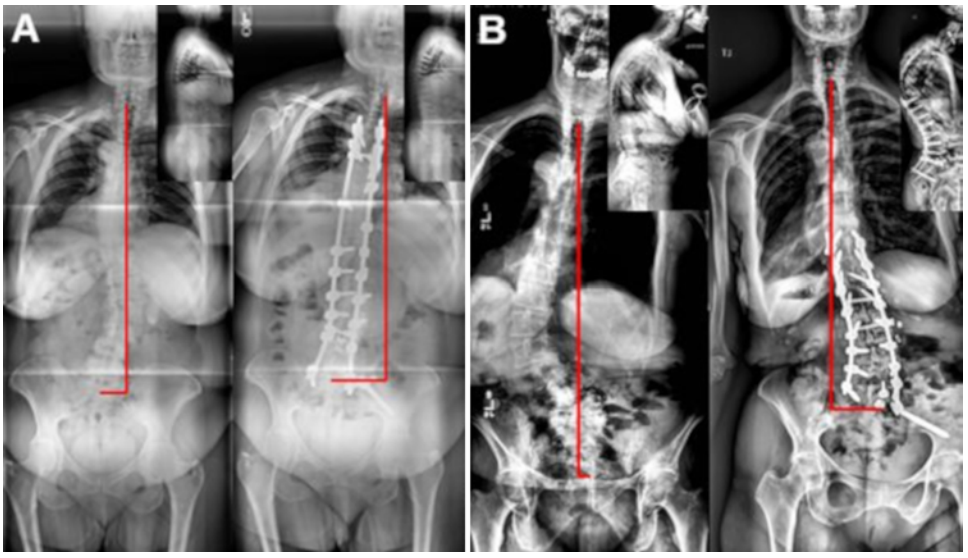

FIG. 1. Standing scoliosis radiographs of 2 patients included this study, demonstrating postoperative global coronal deterioration ≥ 1 cm. Index operations involved long posterior instrumented fusion extending from the sacropelvis to UT spine (**A**) and LT spine (**B**). The measured magnitude of worsening GCM was approximately 5 cm in the UT spine and 7 cm in the LT spine. Figure is available in color online only.

ing complications during clinic follow-up and reviewed pertinent records and imaging studies with the treatment teams. Then, data underwent regular auditing at a central research site to ensure accuracy and completeness. All complications were classified according to time of reported occurrence as intraoperative, early (after surgery until 90 days postoperation), and delayed (from 90 days to 2 years postoperation). Complications were also classified as major or minor according to the criteria of Smith et al.[23,24] The present study focused on operative patients with 2-year follow-up data; however, we also reported the complications of eligible operative patients without full 2-year follow-up data to consider the potential confounding effect of loss to follow-up.

Radiographic assessment was based on full-length, free-standing anteroposterior and lateral spine radiographs (36-inch long cassettes) obtained at preoperative baseline and 2-year postoperative follow-up. All radiographic measurements were performed at a central location using validated software (SpineView, ENSAM Laboratory of Biomechanics)[25,26] and standard technique.[27] The assessed measurements included GCA (i.e., magnitude of lateral offset from the center of the sacrum to the C7 plumbline), pelvic obliquity, coronal Cobb angles (UT, thoracic, thoracolumbar, lumbar, lumbosacral), coronal tilt of the L4 superior endplate, C7–S1 SVA, PT, lumbar lordosis (T12–S1), mismatch between pelvic incidence and lumbar lordosis, and TK (T2–12). All preoperative baseline radiographs were analyzed for coronal curve type and sagittal spinopelvic modifiers according to the SRS-Schwab classification of adult thoracolumbar spinal deformity.[28,29] Further analysis of GCA/GCM was performed using the Qiu classification (type A, GCA < 3 cm; type B, GCM > 3 cm toward the major curve concavity; type C, GCM ≥ 3 cm toward the major curve convexity).[3,30] Also, we performed a subanalysis of patients with baseline pelvic obliquity ≥ 2° (absolute value) on the basis of whether pelvic obliquity was in the direction of GCM (potential case of primary pelvic obliquity) or the opposite direction of GCM (potential case of compensatory pelvic obliquity) according to the criteria of Plais et al.[30]

Data and Statistical Analysis

Continuous variables were presented as mean ± SD, and categorical variables were presented as frequency with calculated percentage. The Shapiro-Wilk test was used to assess normality of data, and then parametric or nonparametric tests were performed as appropriate. Univariate analysis utilized the independent samples t-test, paired t-test, Mann-Whitney U-test, Wilcoxon signed-rank test, chi-square test, and Fisher's exact test. All tests were 2-tailed, and $p < 0.05$ was considered statistically significant. Statistical analysis was performed using SPSS version 26.0 (IBM Corp.).

Results

Patient Population

At the time of data extraction, we identified 875 consecutively operated patients who met the study inclusion criteria and were potentially eligible for 2-year follow-up. Of these, 560 (64.0%) patients had complete 2-year follow-up data available for analysis. Approximately one-quarter of patients (25.7% [144/560]) demonstrated worsening GCA ≥ 1 cm at 2-year follow-up (Fig. 2). The distributions of the modifiers included in the SRS-Schwab classification of adult thoracolumbar spinal deformity are summarized in Supplemental Fig. 1 for these 144 global coronally decompensated patients.[28,29] There were significant differences in the distributions of the coronal curve–type descriptors be-

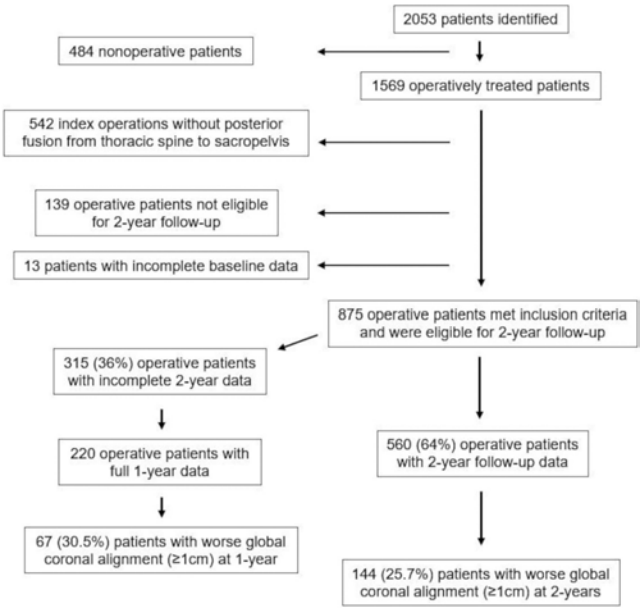

FIG. 2. Flow diagram for patient selection in this study.

TABLE 1. Baseline data of 144 patients with worsening GCA ≥ 1 cm at 2-year follow-up after ASD surgery

Characteristic	All Pts (n = 144)	UT UIV (n = 51)	LT UIV (n = 93)	p Value*
Age at index surgery, yrs	63.4 ± 9.2	61.6 ± 9.9	64.5 ± 8.6	**0.008**
Female sex	111 (77.6)	43 (84.3)	68 (73.9)	0.153
BMI, kg/m^2	28.3 ± 5.8	28.0 ± 5.4	28.4 ± 6.0	0.614
Prior spine fusion	53 (36.8)	15 (29.4)	38 (40.9)	0.173
CCI	2.0 ± 1.6	2.1 ± 1.8	2.0 ± 1.5	0.903
≥1 comorbidity	93 (64.6)	34 (66.7)	59 (63.4)	0.699
No. of comorbidities	2.4 ± 1.6	2.4 ± 1.7	2.3 ± 1.6	0.840
Arthritis	72 (50.0)	25 (49.0)	47 (50.5)	0.862
Hypertension	59 (41.0)	17 (33.3)	42 (45.2)	0.167
Depression	37 (25.7)	14 (27.5)	23 (24.7)	0.721
Osteoporosis	33 (22.9)	18 (35.3)	15 (16.1)	**0.009**
Gastric ulcer	27 (18.8)	12 (23.5)	15 (16.1)	0.277
Smoker	6 (4.2)	1 (2.0)	5 (5.4)	0.417
ASD frailty index	3.6 ± 1.5	3.5 ± 1.4	3.7 ± 1.5	0.518

CCI = Charlson Comorbidity Index.
Boldface type indicates statistical significance. Values are shown as mean ± SD or number (percentage) unless indicated otherwise.
* Comparison between the UT (T1–6) and LT (T7–12) UIV groups was performed using the Mann-Whitney U-test, independent samples t-test, chi-square test, or Fisher's exact test, as appropriate.

tween the UT and LT groups ($p < 0.001$), reflecting greater baseline coronal deformity in the UT group. There were no significant differences in the distributions of the sagittal modifiers between the UT and LT groups.

Among the entire study cohort, 51 (35.4%) patients had UT UIV and 93 (64.6%) patients had LT UIV. Table 1 summarizes the baseline data, including demographic characteristics, history of spine fusion, and reported comorbidities. For the entire cohort, the mean ± SD age was 63.4 ± 9.2 years, most patients were women (111 [77.6%]), and the mean ± SD BMI was 28.3 ± 5.8 kg/m^2 (i.e., overweight). The most common reported comorbidities included arthritis (72 patients [50.0%]), hypertension (59 [41.0%]), depression (37 [25.7%]), osteoporosis (33 [22.9%]), and gastric ulcer (27 [18.8%]). UT patients were younger (61.6 ± 9.9 vs 64.5 ± 8.6 years, $p = 0.008$) and a greater proportion had osteoporosis (35.3% vs 16.1%, $p = 0.009$). ASD frailty index scores[31] were comparable between UT and LT groups.

Index Operative Data

Index operations are summarized in Table 2. UT patients had significantly more posterior fused levels (16.4 ± 0.9 vs 9.7 ± 1.2 levels, $p < 0.001$) and longer operative duration (8.6 ± 3.2 vs 7.6 ± 3.0 hours, $p = 0.023$). Comparisons of the other index operative variables demonstrated no statistically significant differences.

Coronal Radiographic Parameters

Coronal radiographic measurements at baseline and 2-year postoperative follow-up are presented in Table 3. For the entire cohort, GCA significantly worsened by mean ± SD 2.7 ± 1.4 cm from baseline, from 1.9 ± 1.9 cm to 4.6 ± 2.2 cm at 2-year follow-up ($p < 0.001$). These results demonstrated worsening GCA, by a factor of approximately 2.4 times greater from baseline preoperative GCA. For the entire cohort, all other assessed 2-year postoperative coronal parameters significantly improved from baseline, except pelvic obliquity. In comparison with the LT group, the UT group was associated with significantly worse scoliosis at baseline and 2-year follow-up (Table 3).

Qiu Classification

Supplemental Table 1 presents an analysis of GCA/GCM based on the novel Qiu classification. The results demonstrated no statistically significant differences in Qiu type between the UT and LT groups.[3,30]

Subanalysis of Pelvic Obliquity

Supplemental Table 2 presents the subanalysis of 72 patients with preoperative pelvic obliquity ≥ 2° (absolute value).

Sagittal Radiographic Parameters

Sagittal radiographic measurements at baseline and 2-year postoperative follow-up are presented in Table 3. For all patients, the assessed sagittal measurements significantly improved from baseline to 2-year follow-up. The UT group had significantly smaller 2-year postoperative SVA compared with the LT group (2.7 ± 5.7 cm vs 4.7 ± 5.7 cm, $p = 0.014$).

Clinical Outcomes and MCID

HRQL scores at baseline and 2-year follow-up are

TABLE 2. Index operative data of 144 patients with worsening GCA ≥ 1 cm at 2-year follow-up after ASD surgery

Parameter	All Pts (n = 144)	UT UIV (n = 51)	LT UIV (n = 93)	p Value*
Approach				
Posterior only	99 (68.8)	32 (62.7)	67 (72.0)	0.250
Anterior-posterior	45 (31.3)	19 (37.3)	26 (28.0)	0.250
Posterior levels fused	12.1 ± 3.4	16.4 ± 0.9	9.7 ± 1.2	**<0.001**
LIV location				
Sacrum	15 (10.4)	3 (5.9)	12 (12.9)	0.187
Ilium	129 (89.6)	48 (94.1)	81 (87.1)	0.187
Any osteotomy	103 (71.5)	38 (74.5)	65 (69.9)	0.557
SPO	86 (59.7)	31 (60.8)	55 (59.1)	0.847
No./pt	4.9 ± 2.7	6.0 ± 3.3	4.3 ± 2.0	
3CO	25 (17.4)	13 (25.5)	12 (12.9)	0.057
No./pt	1.0 ± 0	1.0 ± 0	1.0 ± 0	
Interbody fusion†	96 (66.7)	32 (62.7)	64 (68.8)	0.460
TLIF	49 (34.0)	16 (31.4)	33 (35.5)	0.885
No./pt	1.4 ± 0.7	1.3 ± 1.0	1.5 ± 0.5	
ALIF	34 (23.6)	12 (23.5)	22 (23.7)	0.986
No./pt	2.1 ± 1.3	3.0 ± 1.5	1.7 ± 0.9	
Op duration, hrs‡	7.9 ± 3.1	8.6 ± 3.2	7.6 ± 3.0	**0.023**
EBL, L‡	2.1 ± 1.6	2.2 ± 1.5	2.0 ± 1.7	0.254
LOS, days	8.1 ± 4.4	8.3 ± 3.7	8.0 ± 4.7	0.153

3CO = 3-column osteotomy (includes pedicle subtraction osteotomy and vertebral column resection); ALIF = anterior lumbar interbody fusion; EBL = estimated blood loss; LIV = lower instrumented vertebral level; LOS = length of index hospital stay; SPO = Smith-Petersen osteotomy; TLIF = transforaminal lumbar interbody fusion.

Boldface type indicates statistical significance. Values are shown as mean ± SD or number (percent) unless indicated otherwise.

* Comparison between UT and LT UIV groups was performed using the Mann-Whitney U-test, independent samples t-test, chi-square test, or Fisher's exact test, as appropriate.

† The majority of interbody fusion procedures were ALIF or TLIF, but extreme lateral interbody fusion, posterior lateral interbody fusion, and TranS1 were also performed in this cohort.

‡ Includes all stages of the index procedure (e.g., anterior and posterior stages).

presented in Table 4. For all patients, the assessed 2-year postoperative HRQL measures significantly improved from baseline. At 2-year follow-up, the UT group had significantly worse HRQL compared with the LT group in terms of SRS-22r Activity (3.2 ± 1.0 vs 3.6 ± 0.8, p = 0.040) and SRS-22r Satisfaction (3.9 ± 1.1 vs 4.3 ± 0.8, p = 0.021) scores.

Supplemental Table 3 presents the percentages of patients who demonstrated HRQL score improvement ≥ 1 MCID at 2-year follow-up. Significantly fewer UT patients achieved ≥ 1 MCID improvement in NRS–leg pain scores in comparison with the LT group (41.3% vs 62.7%, p = 0.020). The bar chart in Fig. 3 depicts the results of these comparisons of assessed HRQL measures.

Lumbar Stiffness Disability Index

Comparison of UT and LT patients demonstrated no significant differences in associated LSDI scores (Supplemental Table 4).

Complications at 2-Year Follow-up

At 2-year follow-up, 108 (75.0%) patients had ≥ 1 complication, for a total of 208 reported complications. There were 35 patients (24.3%) with 1–4 operative complications (total 53 reoperations), 56 patients (38.9%) with 1–6 major complications (total 77 major complications), and 55 patients (38.2%) with 1–4 minor complications (total 78 minor complications). Supplemental Table 5 summarizes the total reported complications, categories of complications, and time of occurrence. Table 5 presents the percentages of affected patients with a given complication. Each reported complication category had comparable percentages of affected UT and LT patients (p > 0.05).

Overall, there were 53 reoperations in 35 (24.3%) patients. For the UT group, there were 30 reoperations involving 18 patients (35.3%), and the most common indication for reoperation was rod fracture (7 reoperations). For the LT group, there were 23 reoperations involving 17 patients (18.3%), and the most common indication for reoperation was proximal junctional kyphosis (8 reoperations). Univariate analysis demonstrated that the percentage of reoperated patients was significantly greater for UT patients compared with LT patients (35.3% vs 18.3%, p = 0.023). The reoperation rate was significantly higher for UT patients compared with that of LT patients for rod fracture (13.7% vs 2.2%, p = 0.006) and pseudarthrosis (7.8% vs 1.1%, p = 0.006), but there was no significant difference in the reoperation rates for proximal junctional kyphosis (9.8% vs 8.6%, p = 0.810).

Complications of Eligible Patients With Incomplete 2-Year Radiographic Follow-up

Of 875 potentially eligible operative patients identified at the time of data extraction, 315 (36.0%) had incomplete 2-year radiographic follow-up data (Fig. 2). Of these patients, 220 had 1-year radiographic follow-up data available for analysis, which demonstrated that 67 (30.5%) patients had worsening GCA ≥ 1 cm (Fig. 2). For these 67 patients (37.3% of UT patients and 62.7% of LT patients), 1-year GCA was worse by an average 2.5 cm from baseline (1.6 ± 1.4 cm to 4.1 ± 1.7 cm, p < 0.001). Supplemental Table 6 summarizes the total reported complications by category and time of occurrence for these 67 patients. Forty-three (64.2%) patients had ≥ 1 complication, for a total of 92 reported complications. There were 13 patients (19.4%) with 1–5 operative complications (total 21 reoperations), 21 patients (31.3%) with 1–6 major complications (total 31 major complications), and 25 patients (37.3%) with 1–4 minor complications (total 40 minor complications).

Discussion

Clinical outcomes research on substantial ASD has focused on sagittal spinopelvic malalignment and restoration.[32–34] The culmination of these research efforts has unveiled a deeper understanding of the significant health impact of ASD,[35–37] and ultimately, the potential benefits that can be achieved by afflicted patients after harmoni-

TABLE 3. Radiographic data of 144 patients with worsening GCA ≥ 1 cm at 2-year follow-up after ASD surgery

Parameters	All Pts (n = 144)	UT UIV (n = 51)	LT UIV (n = 93)	p Value*
Coronal				
GCA, cm				
Baseline	1.9 ± 1.9	2.1 ± 1.9	1.9 ± 1.9	0.574
2-yr FU	4.6 ± 2.2	4.8 ± 2.4	4.5 ± 2.1	0.555
p value†	**<0.001**	**<0.001**	**<0.001**	
Pelvic obliquity, °				
Baseline	2.5 ± 2.0	2.6 ± 2.0	2.4 ± 2.0	0.493
2-yr FU	2.2 ± 1.8	2.2 ± 1.9	2.3 ± 1.7	0.476
p value†	0.184	0.064	0.511	
Cobb angle, °				
Max				
Baseline	39.3 ± 20.8	51.9 ± 22.5	32.5 ± 16.3	**<0.001**
2-yr FU	18.0 ± 14.8	25.2 ± 18.6	14.0 ± 10.4	**<0.001**
p value†	**<0.001**	**<0.001**	**<0.001**	
UT				
Baseline	16.9 ± 9.8	20.4 ± 11.3	12.8 ± 5.8	**0.003**
2-yr FU	13.1 ± 9.5	14.6 ± 11.0	11.6 ± 7.7	0.284
p value†	**0.001**	**<0.001**	0.407	
Thoracic				
Baseline	24.7 ± 18.6	36.7 ± 21.3	16.2 ± 9.9	**<0.001**
2-yr FU	14.6 ± 13.3	21.4 ± 16.3	9.7 ± 7.7	**<0.001**
p value†	**<0.001**	**<0.001**	**<0.001**	
Thoracolumbar				
Baseline	30.7 ± 23.0	42.7 ± 26.7	24.7 ± 18.5	**0.002**
2-yr FU	14.6 ± 15.2	21.2 ± 20.4	11.3 ± 10.4	0.065
p value†	**<0.001**	**<0.001**	**<0.001**	
Lumbar				
Baseline	35.5 ± 18.4	47.3 ± 21.4	30.3 ± 14.2	**0.001**
2-yr FU	15.4 ± 11.2	22.0 ± 12.5	12.5 ± 9.3	**0.001**
p value†	**<0.001**	**<0.001**	**<0.001**	
Lumbosacral				
Baseline	15.7 ± 8.3	17.1 ± 8.3	14.7 ± 8.3	0.210
2-yr FU	7.2 ± 6.3	7.3 ± 5.5	7.2 ± 6.9	0.501
p value†	**<0.001**	**<0.001**	**<0.001**	
L4 tilt, °				
Baseline	17.7 ± 10.8	21.4 ± 11.0	15.7 ± 10.2	**0.003**
2-yr FU	9.6 ± 6.9	10.7 ± 7.8	9.0 ± 6.2	0.292
p value†	**<0.001**	**<0.001**	**<0.001**	
Sagittal				
C7–S1 SVA, cm				
Baseline	6.9 ± 6.5	6.9 ± 6.7	7.0 ± 6.5	0.736
2-yr FU	4.0 ± 5.8	2.7 ± 5.7	4.7 ± 5.7	**0.014**
p value†	**<0.001**	**<0.001**	**0.001**	
PT, °				
Baseline	25.9 ± 9.8	26.6 ± 11.4	25.6 ± 8.9	0.587
2-yr FU	22.4 ± 10.5	22.4 ± 11.0	22.4 ± 10.4	0.975
p value†	**<0.001**	**0.001**	**<0.001**	
PI-LL mismatch, °				
Baseline	18.3 ± 18.6	15.4 ± 21.5	19.9 ± 16.6	0.172
2-yr FU	3.7 ± 15.4	4.2 ± 16.6	3.5 ± 14.8	0.687
p value†	**<0.001**	**<0.001**	**<0.001**	

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TABLE 3. Radiographic data of 144 patients with worsening GCA ≥ 1 cm at 2-year follow-up after ASD surgery

Parameters	All Pts (n = 144)	UT UIV (n = 51)	LT UIV (n = 93)	p Value*
T12–S1 lumbar lordosis, °				
Baseline	33.0 ± 19.2	33.1 ± 23.5	32.9 ± 16.5	0.956
2-yr FU	50.0 ± 14.9	49.9 ± 15.6	50.0 ± 14.6	0.946
p value†	**<0.001**	**<0.001**	**<0.001**	
T2–12 TK, °				
Baseline	–36.9 ± 18.3	–41.0 ± 20.8	–34.6 ± 16.4	0.059
2-yr FU	–53.8 ± 17.1	–55.2 ± 17.5	–53.1 ± 17.0	0.487
p value†	**<0.001**	**<0.001**	**<0.001**	

FU = follow-up; PI-LL = mismatch between pelvic incidence and lumbar lordosis.
Boldface type indicates statistical significance. Values are shown as mean ± SD unless indicated otherwise.
* Comparison between the UT and LT UIV groups was performed using the Mann-Whitney U-test or independent samples t-test.
† Comparison between baseline and 2-year FU measures was performed using the Wilcoxon signed-rank test or paired t-test.

ous restoration and correction of sagittal spinal malalignment.[33,38–40] However, ASD is often characterized by multiaxial spinal malalignment, and in comparison with the sagittal plane, less progress has been made toward understanding coronal malalignment and its clinical impact may have been underestimated.[30,41] Furthermore, surgical correction of GCM can be challenging, and recent evidence suggests that insufficient GCM correction is not a negligible phenomenon for ASD patients.[2,3,5,41] Although GCM may occur less frequently than sagittal spinopelvic malalignment at baseline, this global coronal metric has been reported as one of the most likely deteriorated radiographic parameters after ASD surgery.[1] Therefore, persistent or worsening GCM, as well as iatrogenic GCM appearing in previously balanced patients, can be problematic and contribute to an overall postoperative prevalence rate that is similar to baseline.[1] Some studies have demonstrated that residual or postoperative GCM occurs in approximately 15%–30% of operatively treated ASD patients.[1–4,42] As such, more research is needed to improve our understanding of this common postoperative complication so appropriate operative strategies and novel techniques can be developed to prevent its occurrence.

For ASD patients with residual GCM, it is currently unclear whether certain operative variables, such as fusion length or UIV selection, impact outcomes. Notably, a recent study of ASD patients with this postoperative complication reported no significant differences between UT and LT surgical groups.[2] However, this study primarily focused on identifying risk factors of postoperative GCM, and the authors acknowledged study limitations, such as single-surgeon retrospective design, small sample size, and short 6-month follow-up.[2] Given the recent increase in coronally focused ASD studies,[2,3,30] a multicenter investigation of postoperative GCM with comparisons of UT versus LT could provide novel results regarding potential utility to ASD surgeons. Therefore, the present study assessed International Spine Study Group (ISSG) prospective multicenter operative data with minimum 2-year follow-up duration. Our objective was to first identify operatively treated patients with worsening GCM, and then to compare associated outcomes between UT and LT groups. Because the study inclusion criteria indicated sacropelvic fixation, UIV selection represented a proxy indicator of fusion length.

In the present study, worsening postoperative GCM occurred in 25.7% of surgically treated ASD patients at 2-year follow-up. This result is within the range of postoperative GCM rates reported by previous studies.[1–4,42] Of note, these prior studies used various criteria to define GCM or global coronal deterioration, and the present study utilized criteria similar to those of Daubs et al. (i.e., worsening GCA ≥ 1 cm after surgery).[42] Our results demonstrated that the average magnitude of global coronal deterioration was nearly 3 times the minimum 1-cm criterion for study inclusion (mean ± SD GCA deterioration 2.7 ± 1.4 cm, baseline GCA 1.9 cm, 2-year follow-up GCA 4.6 cm). Among these patients with worse GCM after surgery, UT patients reported significantly worse 2-year HRQL compared with LT patients. Specifically, SRS-22r Activity (score difference ≥ 1 MCID) and SRS-22r Satisfaction scores were significantly different between study groups. Also, significantly fewer patients in the UT group (41.3% vs 62.7%) achieved ≥ 1 MCID improvement in NRS–leg pain scores. These findings are novel because previous investigations generally demonstrated similar HRQL outcomes between UT and LT surgical cohorts with ASD.[7,9,10] Collectively, this could be interpreted as supporting evidence of our study hypothesis that postoperative worsening of GCM or deterioration is clinically less tolerated after long UT fusion (vs LT fusion) for ASD. Also, these results may inform surgical decision-making, such as UIV selection, and potentially improve patient counseling, especially for patients with positive risk factors for postoperative GCM (e.g., osteoporosis, Qiu type C GCM).[3,4]

We suspect that the explanation for these results (worse HRQL of UT patients) is likely multifactorial and could potentially include demographic or radiographic differ-

TABLE 4. HRQL measures at baseline and postoperative 2-year follow-up*

Parameter	All Pts	UT UIV	LT UIV	p Value†
ODI				
Baseline	47.1 ± 15.1	45.5 ± 16.0	46.8 ± 14.0	0.284
2-yr FU	28.9 ± 19.0	32.3 ± 20.0	25.8 ± 18.0	0.074
p value‡	**<0.001§**	**<0.001§**	**<0.001§**	
SF-36				
PCS				
Baseline	29.9 ± 7.9	30.9 ± 7.6	30.1 ± 7.9	0.400
2-yr FU	37.9 ± 10.5	36.6 ± 10.6	39.3 ± 10.3	0.264
p value‡	**<0.001§**	**<0.001**	**<0.001§**	
MCS				
Baseline	44.5 ± 13.6	44.3 ± 12.9	45.9 ± 13.8	0.925
2-yr FU	49.1 ± 14.1	47.6 ± 14.8	49.9 ± 13.7	0.405
p value‡	**0.001**	**0.038**	**0.006**	
SRS-22r				
Activity				
Baseline	2.7 ± 0.8	2.8 ± 0.9	2.8 ± 0.8	0.573
2-year FU	3.4 ± 0.9	3.2 ± 1.0	3.6 ± 0.8	**0.040§**
p value‡	**<0.001§**	**<0.001§**	**<0.001§**	
Pain				
Baseline	2.3 ± 0.8	2.4 ± 0.7	2.2 ± 0.8	0.064
2-yr FU	3.3 ± 1.1	3.1 ± 1.1	3.4 ± 1.1	0.232
p value‡	**<0.001§**	**<0.001§**	**<0.001§**	
Appearance				
Baseline	2.3 ± 0.7	2.2 ± 0.6	2.4 ± 0.7	0.092
2-yr FU	3.4 ± 0.9	3.3 ± 0.8	3.5 ± 0.9	0.097
p value‡	**<0.001§**	**<0.001§**	**<0.001§**	
Mental				
Baseline	3.4 ± 0.9	3.5 ± 0.9	3.4 ± 0.8	0.647
2-yr FU	3.8 ± 1.0	3.7 ± 1.0	3.9 ± 0.9	0.613
p value‡	**<0.001**	**0.006**	**<0.001§**	
Satisfaction				
Baseline	2.8 ± 1.1	3.0 ± 1.0	2.7 ± 1.1	0.360
2-yr FU	4.1 ± 0.9	3.9 ± 1.1	4.3 ± 0.8	**0.021**
p value‡	**<0.001**	**<0.001**	**<0.001**	
Total				
Baseline	2.7 ± 0.6	2.7 ± 0.6	2.7 ± 0.6	0.532
2-yr FU	3.5 ± 0.8	3.4 ± 0.8	3.7 ± 0.8	0.083
p value‡	**<0.001**	**<0.001**	**<0.001**	
NRS				
Back pain				
Baseline	7.5 ± 2.0	7.6 ± 1.8	7.5 ± 2.1	0.916
2-yr FU	3.9 ± 3.2	4.3 ± 3.2	3.7 ± 3.3	0.366
p value‡	**<0.001§**	**<0.001§**	**<0.001§**	
Leg pain				
Baseline	5.2 ± 3.3	4.6 ± 3.3	5.6 ± 3.3	0.087
2-yr FU	2.9 ± 3.1	2.9 ± 2.9	3.0 ± 3.2	0.889
p value‡	**<0.001§**	**<0.001§**	**<0.001§**	

FU = follow-up.

Boldface type indicates statistical significance. Values are shown as mean ± SD unless indicated otherwise.

* Postoperative 2-year FU data were available for ODI (n = 137), SF-36 PCS (n = 128), SF-36 MCS (n = 128), SRS Activity (n = 135), SRS Pain (n = 135), SRS Appearance (n = 134), SRS Mental (n = 134), SRS Satisfaction (n = 131), SRS Total (n = 135), NRS–back pain (n = 132), and NRS–leg pain (n = 133).

† Comparison between UT and LT UIV groups was performed using the Mann-Whitney U-test or independent samples t-test.

‡ Comparison between baseline and 2-year FU scores was performed using the Wilcoxon signed-rank test or paired t-test.

§ Denotes significant p values with mean score ≥ 1 MCID; there is no reported MCID value for SF-36 MCS, SRS-22r Total, and SRS-22r Satisfaction.

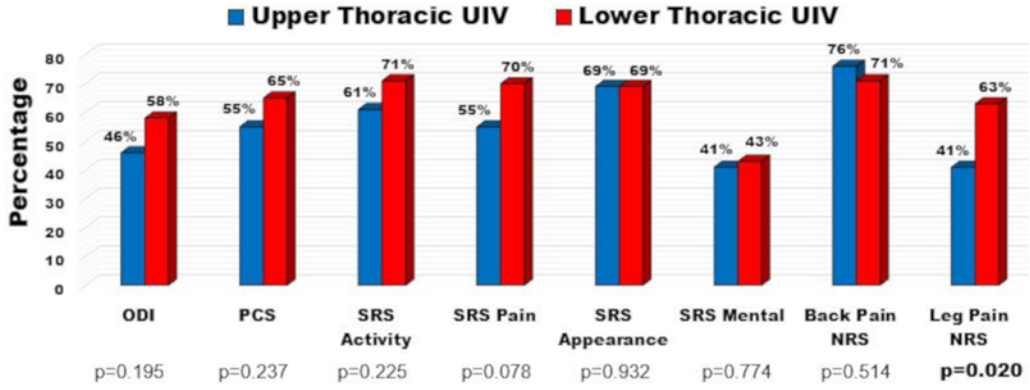

FIG. 3. Bar charts depicting the percentages of patients who demonstrated HRQL improvement ≥ 1 MCID at 2-year follow-up. Postoperative 2-year MCID data were available for ODI (n = 137), SF-36 PCS (n = 122), SRS Activity (n = 133), SRS Pain (n = 133), SRS Appearance (n = 132), SRS Mental (n = 132), NRS–back pain (n = 128), and NRS–leg pain (n = 129). Comparisons of these percentages between the UT and LT groups were performed using the chi-square test, and the resulting p values are indicated. Notably, the UT group included fewer patients who achieved ≥ 1 MCID improvement in NRS–leg pain (41% vs 63%, p = 0.020). Figure is available in color online only.

ences, occurrence of other postoperative complications, and/or possibly greater stiffness-related disability from longer fusion constructs that is exacerbated by worsening coronal malalignment. First, the UT group included a greater percentage of patients with osteoporosis, which has been reported as a possible risk factor of postoperative GCM, and this may have contributed to worse outcomes.[4] Next, the UT group had greater proportions of patients with scoliosis at baseline and postoperation in comparison with the LT group (which we acknowledge is a potential confounder owing to selection bias); however, the UT group maintained a smaller positive C7–S1 SVA, which would likely be associated with better, not worse, outcomes. Of note, these radiographic results are consistent with other ASD studies that compared UT and LT surgical cohorts; that is, patients with UT UIV dem-

TABLE 5. Summary of complications of 144 ASD patients with worsening GCA ≥ 1 cm at 2-year follow-up

Complication	All Pts (n = 144)	UT UIV (n = 51)	LT UIV (n = 93)	p Value*
Medical				
Cardiac	5.6	5.9	5.4	>0.99
Coagulopathy	6.9	7.8	6.5	0.743
Gastrointestinal	5.6	2.0	7.5	0.260
Infection	7.6	9.8	6.5	0.520
Neurological	4.9	2.0	6.5	0.422
Pulmonary	6.9	5.9	7.5	>0.99
Renal	0.7	0.0	1.1	>0.99
Surgical				
Implant failure	15.3	19.6	12.9	0.335
Implant malposition	5.6	7.8	4.3	0.454
Infection	2.8	3.9	2.2	0.615
Operative	18.1	17.6	18.3	>0.99
Neurological	12.5	15.7	10.8	0.435
Wound	4.9	5.9	4.3	0.698
Radiographic Imbalance	29.2	29.4	29.0	0.99

Values are shown as percentages unless indicated otherwise.
*Comparison between UT (T1–6) and LT (T7–12) UIV groups was performed using the chi-square test or Fisher's exact test, as appropriate.

onstrated worse scoliosis and greater SVA correction and tended to maintain smaller positive SVA at postoperative follow-up.[9,10]

The occurrence of postoperative complications (other than global coronal deterioration) may also be related to the lower HRQL scores reported by the UT group. Although the percentages of UT and LT patients affected by various complications were comparable, the UT group demonstrated a higher total reoperation rate, as well as higher reoperation rates for rod fracture and pseudarthrosis. Of note, we acknowledge that these results did not control for the significantly older age of the LT group, nor the higher percentage of patients with osteoporosis in the UT group. However, these operative complications may still manifest as functional limitations that contribute to worse associated HRQL. Alternatively, it is possible that worsening GCA leads to increased biomechanical stress on longer UT fusion constructs, and that the reoperations for rod fracture/pseudarthrosis are a downstream consequence rather than a principal etiologic driver of worse HRQL. Prior studies of ASD complications that compared UT and LT patients have produced mixed results, with some reporting more perioperative complications, higher pseudarthrosis rates, and more revision surgical procedures for UT patients,[8] and others reporting similar overall rates of complications and reoperations between UT and LT patients.[7,10]

Next, spinal stiffness related to long fusion from the sacropelvis to proximal thoracic spine may also have partly contributed to the worse HRQL of the UT group. Although UT patients had greater LSDI scores, the difference was not statistically different compared with those of LT patients. In general, this result is consistent with other ASD studies that demonstrated few functional differences between UT and LT surgical cohorts on the basis of LSDI analysis.[11,12] It is important to note that these other studies did not focus on cohorts of coronally imbalanced patients, and so it may be possible that LSDI could not detect functional differences in our study. In addition, complete LSDI data were not available for all study patients. Therefore, we hypothesize that the demonstrated HRQL differences in this study were likely related to complex interplay between global coronal deterioration and limited compensatory mechanisms that were impaired by longer fusion, spinal stiffness, and back/leg pain. We acknowledge that further research is needed to elucidate the pathophysiology of global coronal decompensation and its asymmetrical impact on UT fusion (in comparison with LT fusion) that was demonstrated by our study findings.

In a recent study, Plais et al. suggested that pelvic obliquity was likely an important parameter to assess when determining the impact of GCM.[30] The authors described cases where pelvic obliquity was likely a compensatory mechanism for GCM, analogous to compensatory high PT for positive global sagittal malalignment.[30] As such, we performed a subanalysis of patients with baseline pelvic obliquity ≥ 2° on the basis of the direction of pelvic obliquity and GCM. In this study, potential primary pelvic obliquity was indicated when pelvic obliquity and GCM were in the same direction, whereas potential compensatory pelvic obliquity was indicated when pelvic obliquity and GCM were in opposite directions. As might have been expected, baseline global coronal deformity was significantly less in the subgroup of patients with compensatory pelvic obliquity; however, there was no significant difference at 2 years postoperation. Of note, we acknowledge that this study was not designed to fully elucidate the compensatory mechanisms of pelvic obliquity and its potential interaction with GCM. However, we still think it is important to know that in some patients with ASD and baseline pelvic obliquity due to primary pathology (not coronal compensation), long spine fusion associated with adequate standing GCA may cause poor results when the patient sits and leveling of the ischial tuberosities occurs.

The strengths of this study include prospective data collection and multicenter design methodology, with onsite study coordinators and centralized auditing to ensure data accuracy and completeness. We think these results may inform operative decision-making (e.g., UIV selection) and improve patient counseling. It is important to keep in mind that all assessed HRQL outcome measures improved in the present study. Also, improvement ≥ 1 MCID on various HRQL instruments was achieved by 42%–73% of study patients, which is similar to other reports.[38] Therefore, when counseling ASD patients who are at risk for global coronal worsening, it may be appropriate to provide reassurance of expected improvement in associated HRQL outcome measures, as well as to acknowledge that the occurrence of this postoperative complication may differentially impact clinical outcomes on the basis of the surgeon's operative selection of UIV.

The limitations of the present study include its retrospective analysis despite prospective collection of multicenter data. The study focused on 144 patients, which may be a relatively small sample size and may limit the generalizability of our findings. Also, a potential limitation may be that significant differences in HRQL were demonstrated for the subdomains of SRS-22r (Activity and Satisfaction) rather than SRS-22r Total and/or ODI. Next, complete 2-year follow-up data were available for 64% (560/875) of potentially eligible patients. To assess potential bias (from loss to follow-up) and to determine if the occurrence of complications may have been related to loss to follow-up, the remaining 315 patients were analyzed using 1-year data. Of these 315 patients, 220 had complete 1-year follow-up data; of these patients, 67 (30.5%) patients demonstrated global coronal decompensation. For these 67 patients, there did not appear to be a disproportionate rate of complications that may explain loss to follow-up. Overall, approximately 90% (780/875) of potentially eligible patients in this study were analyzed using either 1-year or 2-year follow-up data. Finally, our subanalysis excluded patients who did not demonstrate worsening GCA ≥ 1 cm and may have provided novel data for comparison of outcomes with the primary cohort of this study. However, it is important to note that many other studies of ASD have generally demonstrated similar outcomes when comparing UT and LT fusion groups (without focusing on coronal alignment/malalignment). As such, the results of this study could be interpreted as supportive evidence that postoperative worsening of GCM or deterioration is clinically less tolerated after long UT fusion (in comparison with LT fusion) for ASD.

Conclusions

This ASD study provided a multicenter assessment of postoperative worsening of GCM and its potential impact on outcomes of long sacropelvic fusion with UT or LT proximal fixation. Overall, the assessed HRQL measures improved at 2-year follow-up, and comparative analysis demonstrated significant differences in HRQL between the UT and LT surgical groups. Despite having significantly smaller positive SVA at follow-up, patients with UT fusion had worse 2-year SRS-22r Activity score, worse SRS-22r Satisfaction score, and lower rate of MCID improvement in NRS–leg pain score. Also, the overall reoperation rate was higher for the UT group, and this included higher reoperation rates for rod fracture and pseudarthrosis. Collectively, these findings may represent initial progress and preliminary evidence suggesting that worsening GCM after ASD surgery is likely less tolerated in patients who undergo longer UT fusion (in comparison with LT fusion). Although further research is needed to clarify the pathophysiology of this complication, the current results may better inform operative decision-making and improve patient counseling.

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Disclosures

The International Spine Study Group (ISSG) is funded through research grants from DePuy Synthes. Dr. Shaffrey is a consultant for Medtronic, NuVasive, and SI Bone; owns stock in NuVasive; holds patents with Medtronic, NuVasive, and Zimmer Biomet; and receives royalties from NuVasive. Dr. Klineberg is a consultant for DePuy Synthes, Stryker, and Medicrea/Medtronic; receives honoraria from AO Spine; and has a fellowship grant from AO Spine. Dr. Lafage is a consultant for Globus Medical; receives royalties from NuVasive; receives honoraria from The Permanente Group, DePuy Synthes, Implanet, and J&J; and owns stock in Nemaris Inc. Mr. Lafage owns stock in Nemaris. Dr. Protopsaltis is a consultant for Globus, Stryker K2M, NuVasive, Medicrea, and Medtronic; receives royalties from Altus; and owns stock options in SpineAlign and Torus Medical. Dr. Passias is a consultant for Terumo, SpineWave, Royal Biologics, and Medicrea; is on the speakers bureau of Zimmer and Globus Medical; and receives clinical or research support for the study described from Allosource and cSRS. Dr. Mundis is a consultant for NuVasive, K2M/Stryker, Viseon, SeaSpine, and Carlsmed; owns stock in NuVasive, Carlsmed, Viseon, SeaSpine, and Alphatec; receives royalties from NuVasive and K2M/Stryker; and holds patents with K2M/Stryker. Dr. Eastlack owns stock in Spine Innovation, Alphatec, SeaSpine, and NuVasive; is a consultant for NuVasive, SeaSpine, SI Bone, Stryker, Medtronic, and Spinal Elements; holds patents with Spine Innovation, Globus, and Stryker; is on the speakers bureau of Radius; receives royalties from Globus, SeaSpine, NuVasive, and SI Bone; and receives non–study-related clinical or research support from NuVasive, SeaSpine, and Medtronic. Dr. Deviren is a consultant for NuVasive, Biomet, SeaSpine, Medicrea, and Alphatec; receives royalties from NuVasive; receives institutional fellowship support NuVasive; and owns stock in Omega. Dr. Kelly receives non–study related clinical or research support from DePuy/Synthes Spine and receives honoraria from *The Journal of Bone and Joint Surgery*. Dr. Daniels is a consultant for Spineart, Stryker, Medtronic, Medicrea, EOS, and Orthofix and receives royalties from Spineart, Medicrea, and Springer. Dr. Gum is an employee of Norton Healthcare; is a consultant for Medtronic, Acuity, K2M/Stryker, NuVasive, and Mazor; is on the speakers bureau of DePuy; receives royalties from Acuity and NuVasive; receives honoraria from Pacira Pharmaceuticals, Baxter, Broadwater, and NASS; receives clinical or research support for the study described from Integra, Intellirod Spine Inc, Pfizer, ISSG, NuVasive, and Norton Healthcare; owns stock in Cingulate Therapeutics; holds patents with Medtronic; and serves on the advisory/editorial boards of K2M/Stryker, Medtronic, and National Spine Health. Dr. Gupta owns stock in J&J and P&G; receives royalties from Innomed, Globus, and DePuy; is a consultant for DePuy, Medtronic, and Globus; receives honoraria from AO Spine; and receives travel reimbursements from DePuy, Medtronic, SRS, AO Spine, Medicrea, Mizuho, and Alphatec. Dr. Burton owns stock in Progenerative Medical; receives royalties from DePuy; and receives clinical or research support for the study described from DePuy. Dr. Schwab is a consultant for ZimmerBiomet, MSD, and K2M; receives royalties from ZimmerBiomet, MSD, and Medicrea; and serves on the executive committee of ISSG. Dr. Bess is a consultant for K2 Stryker and Mirus; owns stock in Progenerative Medical and Carlsmed; holds patents with K2 Stryker and NuVasive; receives clinical or research support for the study described from ISSGF, K2 Stryker, NuVasive, and DePuy Synthes; receives non–study-related clinical or research support from ISSGF, NuVasive, Medtronic, DePuy Synthes, K2 Stryker, SI Bone, and SeaSpine; and receives royalties from K2 Stryker and NuVasive. Dr. Ames is an employee of UCSF; receives royalties from Stryker, Biomet Zimmer Spine, DePuy Synthes, NuVasive, Next Orthosurgical, K2M, and Medicrea; owns stock in DePuy Synthes; is a consultant for Medtronic, Medicrea, K2M, and Titan Spine; receives research support from Titan Spine, DePuy Synthes, and ISSG; serves on the editorial board of *Operative Neurosurgery*; receives grant funding from SRS; serves on the executive committee of ISSG; and serves as the director of Global Spinal Analytics. Dr. Smith is a consultant for Cerapedics, Carlsmed, Stryker, DePuy Synthes, NuVasive, and Zimmer Biomet; receives royalties from Zimmer Biomet, NuVasive, and Thieme; receives clinical or research support for the study described from DePuy Synthes and ISSGF; receives non–study-related clinical or research support from DePuy Synthes, ISSGF, NuVasive, and AO Spine; owns stock in NuVasive and Alphatec; and receives fellowship funding from AO Spine.

Author Contributions

Conception and design: all authors. Acquisition of data: Shaffrey,

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Supplemental Information

Online-Only Content

Supplemental material is available with the online version of the article.

Supplemental Figure and Tables. https://thejns.org/doi/suppl/10.3171/2021.2.SPINE201938.

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