

Multicenter assessment of surgical outcomes in adult spinal deformity patients with severe global coronal malalignment: determination of target coronal realignment threshold

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OBJECTIVE The impact of global coronal malalignment (GCM; C7 plumb line–midsacral offset) on adult spinal deformity (ASD) treatment outcomes is unclear. Here, the authors' primary objective was to assess surgical outcomes and complications in patients with severe GCM, with a secondary aim of investigating potential surgical target coronal thresholds for optimal outcomes.

METHODS This is a retrospective analysis of a prospective multicenter database. Operative patients with severe GCM (≥ 1 SD above the mean) and a minimum 2-year follow-up were identified. Demographic, surgical, radiographic, health-related quality of life (HRQOL), and complications data were analyzed.

RESULTS Of 691 potentially eligible operative patients (mean GCM 4 ± 3 cm), 80 met the criteria for severe GCM ≥ 7 cm. Of these, 62 (78%; mean age 63.7 ± 10.7 years, 81% women) had a minimum 2-year follow-up (mean follow-up 3.3 ± 1.1 years). The mean ASD–Frailty Index was 3.9 ± 1.5 (frail), 50% had undergone prior fusion, and 81% had concurrent severe sagittal spinopelvic deformity with GCM and C7–S1 sagittal vertical axis (SVA) positively correlated

ABBREVIATIONS ASD = adult spinal deformity; ASD-FI = Adult Spinal Deformity–Frailty Index; EBL = estimated blood loss; GCM = global coronal malalignment; HRQOL = health-related quality of life; IBF = interbody fusion; LL = lumbar lordosis; MCID = minimal clinically important difference; MCS = mental component summary of SF-36; NRS = numeric rating scale; ODI = Oswestry Disability Index; PCS = physical component summary of SF-36; PI = pelvic incidence; PI-LL = mismatch between PI and LL; PJK = proximal junctional kyphosis; PT = pelvic tilt; SCB = substantial clinical benefit; SRS = Scoliosis Research Society; SRS-22r = 22-Item SRS Patient Questionnaire; SVA = sagittal vertical axis; TK = thoracic kyphosis; UIV = uppermost instrumented vertebra; 3CO = 3-column osteotomy.

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($r = 0.313$, $p = 0.015$). Surgical characteristics included posterior-only (58%) versus anterior-posterior (42%) approach, mean fusion of 13.2 ± 3.8 levels, iliac fixation (90%), 3-column osteotomy (36%), operative duration of 8.3 ± 3.0 hours, and estimated blood loss of 2.3 ± 1.7 L. Final alignment and HRQOL significantly improved ($p < 0.01$): GCM, 11 to 4 cm; maximum coronal Cobb angle, 43° to 20° ; SVA, 13 to 4 cm; pelvic tilt, 29° to 23° ; pelvic incidence–lumbar lordosis mismatch, 31° to 5° ; Oswestry Disability Index, 51 to 37; physical component summary of SF-36 (PCS), 29 to 37; 22-Item Scoliosis Research Society Patient Questionnaire (SRS-22r) Total, 2.6 to 3.5; and numeric rating scale score for back and leg pain, 7 to 4 and 5 to 3, respectively. Residual GCM ≥ 3 cm was associated with worse SRS-22r Appearance ($p = 0.04$) and SRS-22r Satisfaction ($p = 0.02$). The minimal clinically important difference and/or substantial clinical benefit (MCID/SCB) was met in 43%–83% (highest for SRS-22r Appearance [MCID 83%] and PCS [SCB 53%]). The severity of baseline GCM (≥ 2 SD above the mean) significantly impacted postoperative SRS-22r Satisfaction and MCID/SCB improvement for PCS. No significant partial correlations were demonstrated between GCM or SVA correction and HRQOL improvement. There were 89 total complications (34 minor and 55 major), 45 (73%) patients with ≥ 1 complication (most commonly rod fracture [19%] and proximal junctional kyphosis [PJK; 18%]), and 34 reoperations in 22 (35%) patients (most commonly for rod fracture and PJK).

CONCLUSIONS Study results demonstrated that ASD surgery in patients with substantial GCM was associated with significant radiographic and HRQOL improvement despite high complication rates. MCID improvement was highest for SRS-22r Appearance/Self-Image. A residual GCM ≥ 3 cm was associated with a worse outcome, suggesting a potential coronal realignment target threshold to assist surgical planning.

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KEYWORDS adult spinal deformity; complications; coronal imbalance/malalignment; outcomes; pedicle subtraction osteotomy; scoliosis; spine surgery

SUBSTANTIAL adult spinal deformity (ASD) research has focused on the clinical impact and evaluation of sagittal spinopelvic parameters.^{1–5} Currently, well-defined radiographic alignment thresholds and predictive formulas exist to help surgeons plan sagittal correction.⁶ Less attention has been given to evaluation of ASD in the coronal plane despite early evidence suggesting that more substantial global coronal malalignment (GCM; displacement of C7 plumb line from midsacrum) had a negative impact on pain and function.¹⁷ Recent studies have demonstrated baseline GCM in up to 35% of patients with ASD.^{8,9} Moreover, GCM can worsen postoperatively or can occur as an iatrogenic complication in previously balanced patients.^{9–13} Collectively, these findings suggest that the associated clinical impact of GCM has been underestimated.^{8–10,12–14}

Given increased attention on coronal deformity in the recent ASD literature, an investigation focused on surgical outcomes in a multicenter ASD cohort with severe GCM could provide useful benchmark data, which could assist surgical planning and patient counseling. Therefore, our primary objective was to assess treatment outcomes and complications associated with ASD surgery in patients with severe GCM and a minimum 2-year follow-up. Our secondary aim was to investigate potential surgical realignment goals or thresholds for coronal correction. We hypothesized that ASD surgery in patients with severe GCM is associated with favorable outcomes despite potentially high rates of complications.

Methods

Patient Selection

This was a retrospective review of a prospective multicenter International Spine Study Group database of consecutive ASD patients. Subjects were enrolled into an ongoing database through an IRB-approved protocol at

multiple centers across the United States. Database inclusion criteria were an age ≥ 18 years and ≥ 1 of the following measures: scoliosis $\geq 20^\circ$, C7–S1 sagittal vertical axis (SVA) ≥ 5 cm, pelvic tilt (PT) $\geq 25^\circ$, and thoracic kyphosis (TK) $\geq 60^\circ$. Patients with an active infection, a malignancy, or a diagnosis of scoliosis other than degenerative or idiopathic were excluded (e.g., neuromuscular). At the time of enrollment, patients were subdivided into operative and nonoperative treatment groups based on the initial management decided by the operating surgeon. The current study focuses on patients with severe GCM who underwent operative treatment and had a minimum 2-year follow-up. For this study, severe GCM was defined as a coronal offset magnitude ≥ 1 SD above the mean for all potentially eligible operative patients.

Data Collection, Radiographic Assessment, and Health-Related Quality of Life

Demographic and clinical data, including comorbidities and ASD–Frailty Index (ASD–FI) scores,¹⁵ were collected. Operative data were extracted from standardized collection sheets and included ASD–surgical invasiveness score,¹⁶ use of direct decompression, use of Smith-Petersen osteotomy or 3-column osteotomy (3CO), and use of interbody fusion (IBF). Complications were assessed based on clinical examination, imaging review, and standardized collection forms. Onsite coordinators assisted with data collection, and the data were subjected to regular central auditing to ensure accuracy and completeness. Complications were classified as intraoperative, early (≤ 30 days postoperative), or delayed (> 30 days postoperative) and as major or minor per Smith et al.^{17,18} Although the present study focuses on patients with a minimum 2-year follow-up, we report complications for eligible operative patients who did not have a minimum 2-year follow-up to account for the potential confounding effect of loss to follow-up.

Full-length, free-standing anteroposterior and lateral spine radiographs (36-inch long cassettes) were obtained preoperatively and at specified postoperative time intervals for analysis at a central location using validated software (SpineView, ENSAM Laboratory of Biomechanics).^{19,20} All radiographic measurements were performed based on standard technique²¹ and included GCM, pelvic obliquity, coronal Cobb angles and apices (upper thoracic, thoracic, thoracolumbar, lumbar), SVA, PT, lumbar lordosis (LL; T12–S1), pelvic incidence (PI), mismatch between PI and LL (PI-LL), and TK (T4–12). Radiographs were assessed for measurement by a trained research associate and were reviewed for accuracy and corrected as necessary by senior researchers with extensive experience. All baseline radiographs were analyzed to identify coronal curve types and sagittal spinopelvic modifiers per the Scoliosis Research Society (SRS)–Schwab classification.²²

Health-related quality of life (HRQOL) outcomes were prospectively collected for all patients using standardized questionnaires and included the Oswestry Disability Index (ODI),²³ the SF-36,²⁴ and the 22-Item SRS Patient Questionnaire (SRS-22r).^{25,26} Two standard summary scores were calculated based on the SF-36 and included the physical component summary (PCS) and mental component summary (MCS).²⁴ The SRS-22r instrument provides a total score and 5 subdomain scores: Activity, Pain, Appearance, Mental, and Satisfaction.^{25,26} Severity of back and leg pain were assessed using a numeric rating scale (NRS) with scores ranging from 0 (no pain) to 10 (unbearable pain). Values for minimal clinically important difference (MCID) and substantial clinical benefit (SCB) have been established to provide clinical context when assessing HRQOL.^{27–30} Two-year postoperative HRQOL data were analyzed to determine the percentage of patients attaining MCID and/or SCB thresholds for improvement.

Data and Statistical Analysis

Data are presented as the means \pm standard deviation for continuous variables and frequency with calculated percentages for categorical variables. Data normality was assessed using the Shapiro-Wilk test, and appropriate parametric or nonparametric tests were performed. Univariate analysis included the independent-samples t-test, paired t-test, Mann-Whitney U-test, Wilcoxon signed-rank test, Pearson's chi-square test, and Fisher's exact test. To investigate the impact of GCM versus global sagittal malalignment, a subanalysis was performed using an SVA ≥ 10 cm (severe global sagittal malalignment),^{22,31} and GCM was subdivided into severe and very severe GCM (≥ 2 SD above the mean). Pearson product-moment correlation coefficients were calculated for baseline GCM and other radiographic parameters. Partial correlations and linear regression were performed to assess postoperative HRQOL changes and GCM/SVA correction. An iterative univariate analysis was refined with 1-mm increments to determine the potential threshold magnitude of postoperative GCM (i.e., residual GCM) that was significantly associated with a worse HRQOL. Binary logistic regression was performed to determine possible predictors of residual GCM (based on previous calculations), minimal

postoperative disability (ODI ≤ 20), and the occurrence of a major complication. All tests were two-tailed, and p values < 0.05 were considered statistically significant. Statistical analyses were performed using IBM SPSS Statistics for Windows version 26.0 (IBM Corp.).

Results

Baseline Characteristics, Alignment, and HRQOL

At the time of data extraction, there were 691 potentially eligible operative patients with a mean GCM of 4 ± 3 cm. Eighty of the 691 patients had severe GCM ≥ 7 cm (≥ 1 SD above the mean). Of these 80 patients, 62 (78%) had a minimum 2-year follow-up and were included in our analysis. Table 1 summarizes baseline demographics, comorbidities, biplane alignment, and HRQOL for the 62 patients. Forty patients had a severe SVA ≥ 10 cm,^{22,31} and 27 patients had very severe GCM ≥ 10 cm (≥ 2 SD above the mean).

Overall, the mean age was 63.7 ± 10.7 years and most patients (80.6%) were women (Table 1). The mean BMI was 27.2 ± 6.2 kg/m² (overweight), and the mean baseline ASD-FI score was 3.9 ± 1.5 (frail).¹⁵ Patients with an SVA ≥ 10 cm were significantly more frail (4.2 vs 3.3, $p = 0.038$). Most patients (87.1%) had ≥ 1 comorbidity, and 25.8% had > 3 comorbidities; hypertension (45.2%), depression (32.3%), and osteoporosis (25.8%) were the most commonly reported comorbidities. Notably, 56.5% and 50.0% of patients had undergone previous spine surgery and previous spine fusion, respectively.

Baseline coronal alignment included a mean GCM = 10.5 ± 3.6 cm, thoracic coronal Cobb = $23.1^\circ \pm 16.6^\circ$, thoracolumbar coronal Cobb = $38.3^\circ \pm 21.7^\circ$, and lumbar coronal Cobb = $30.1^\circ \pm 16.7^\circ$ (Table 1). The majority (77%) of patients had coronal curves $> 30^\circ$, with thoracolumbar/lumbar-only (type L, 55%), double (type D, 21%), and thoracic-only (type T, 2%) curve descriptors per the SRS-Schwab classification.²² Baseline sagittal alignment included SVA = 12.9 ± 7.3 cm, PT = $28.6^\circ \pm 11.1^\circ$, LL = $19.9^\circ \pm 20.8^\circ$, and PI-LL = $30.9^\circ \pm 20.3^\circ$. Fifty patients (81%) demonstrated ≥ 1 severely abnormal SRS-Schwab sagittal spinopelvic modifier (PT $> 30^\circ$, SVA > 9.5 cm, PI-LL $> 20^\circ$; Supplemental Fig. 1).²²

The study cohort reported severe disability (mean ODI = 51.0 ± 20.1 ; Table 1).²³ Additional baseline HRQOL measures included PCS = 29.2 ± 9.2 and SRS-22r Activity = 2.6 ± 0.9 , Pain = 2.1 ± 0.8 , Appearance/Self-Image = 2.2 ± 0.7 , Mental = 3.4 ± 0.9 , and Total = 2.6 ± 0.7 . NRS scores for back and leg pain were 7.0 ± 2.4 and 4.8 ± 3.3 , respectively. Patients with an SVA ≥ 10 cm had significantly worse HRQOL ($p < 0.05$) based on the ODI, PCS, and SRS-22r Activity, Pain, and Total.

Baseline Correlations Between GCM and Other Radiographic Parameters

Pearson product-moment coefficients were computed for GCM and all other radiographic parameters at baseline (Supplemental Table 1). Significant correlations included pelvic obliquity ($r = 0.276$, $p = 0.033$), thoracolumbar coronal Cobb ($r = -0.311$, $p = 0.028$), SVA ($r = 0.313$, $p = 0.015$), and PT ($r = -0.478$, $p < 0.001$).

TABLE 1. Baseline demographics, alignment, and HRQOL for all patients and comparisons by baseline SVA and GCM

Variable	All Patients (n = 62)	Comparison by SVA*			Comparison by GCM		
		<10 cm (n = 20)	≥10 cm (n = 40)	p Value†	<10 cm (n = 35)	≥10 cm (n = 27)	p Value†
Age in yrs (SD)	63.7 (10.7)	61.8 (7.2)	64.6 (12.3)	0.065	65.4 (8.0)	61.6 (13.4)	0.293
Female, no. (%)	50 (80.6)	20 (100.0)	29 (72.5)	0.011	28 (80.0)	22 (81.5)	0.884
BMI in kg/m ² (SD)	27.2 (6.2)	26.6 (4.9)	27.7 (6.8)	0.814	27.8 (5.4)	26.5 (7.1)	0.166
CCI (SD)	2.1 (1.7)	1.9 (1.2)	2.0 (1.8)	0.987	2.0 (1.5)	2.2 (1.9)	0.988
ASD-FI (SD)	3.9 (1.5)	3.3 (1.7)	4.2 (1.4)	0.038	3.9 (1.6)	3.9 (1.5)	0.909
No. w/ ≥1 comorbidity (%)	54 (87.1)	18 (90.0)	38 (95.0)	0.595	34 (97.1)	24 (88.9)	0.309
No. of comorbidities (%)							
0	8 (12.9)	2 (10.0)	6 (15.0)	0.707	3 (8.6)	5 (18.5)	0.279
1–3	38 (61.3)	15 (75.0)	23 (57.5)	0.185	24 (68.6)	14 (51.9)	0.180
>3	16 (25.8)	3 (15.0)	11 (27.5)	0.347	8 (22.9)	8 (29.6)	0.546
HTN, no. (%)	28 (45.2)	9 (45.0)	17 (42.5)	0.854	17 (48.6)	11 (40.7)	0.539
Depression, no. (%)	20 (32.3)	5 (25.0)	14 (35.0)	0.432	11 (31.4)	9 (33.3)	0.874
Osteoporosis, no. (%)	16 (25.8)	4 (20.0)	10 (25.0)	0.756	10 (28.6)	6 (22.2)	0.571
Hx spine surgery, no. (%)	35 (56.5)	12 (60.0)	21 (52.5)	0.582	17 (48.6)	18 (66.7)	0.154
Hx fusion, no. (%)	31 (50.0)	10 (50.0)	19 (47.5)	0.855	15 (42.9)	16 (59.3)	0.200
GCM in cm (SD)	10.5 (3.6)	9.4 (2.0)	11.1 (4.2)	0.188	8.3 (9.6)	13.3 (3.9)	<0.001
PO in ° (SD)	2.9 (2.9)	2.4 (2.3)	3.3 (3.2)	0.214	2.4 (2.7)	3.6 (3.0)	0.012
Coronal Cobb in ° (SD)							
Upper thoracic	16.0 (10.0)	17.5 (9.1)	15.0 (10.8)	0.233	19.0 (11.4)	12.6 (7.0)	0.136
Thoracic	23.1 (16.6)	23.0 (11.0)	23.8 (18.7)	0.597	24.0 (18.1)	21.7 (14.7)	0.779
TL	38.3 (21.7)	43.2 (23.0)	36.1 (20.9)	0.274	42.0 (23.4)	32.3 (17.6)	0.101
Lumbar	30.1 (16.7)	32.2 (14.8)	29.4 (18.1)	0.439	27.9 (15.0)	32.5 (18.4)	0.465
SVA in cm (SD)	12.9 (7.3)	5.6 (3.0)	16.6 (6.0)	<0.001	11.7 (6.6)	14.4 (8.0)	0.159
Sagittal plane in ° (SD)							
PT	28.6 (11.1)	24.7 (8.9)	30.4 (12.0)	0.015	30.8 (11.1)	25.6 (10.7)	0.142
LL	19.9 (20.8)	32.5 (18.6)	15.3 (18.5)	0.001	21.2 (20.7)	18.3 (21.1)	0.593
PI	55.0 (11.2)	54.0 (10.2)	55.6 (12.0)	0.814	56.8 (12.7)	52.7 (8.5)	0.290
PI-LL	30.9 (20.3)	16.5 (14.3)	36.5 (18.6)	<0.001	30.7 (19.7)	31.3 (21.4)	0.913
TK	30.6 (15.3)	31.0 (15.4)	30.5 (15.4)	0.912	31.4 (13.6)	29.6 (17.4)	0.648
HRQOL measures							
ODI	51.0 (20.1)	42.8 (22.8)	55.1 (17.9)	0.037	50.4 (19.2)	51.9 (21.5)	0.513
PCS	29.2 (9.2)	34.5 (8.6)	26.7 (8.7)	0.004	30.3 (7.4)	27.6 (11.2)	0.084
MCS	44.8 (14.1)	44.6 (15.2)	44.9 (14.0)	0.941	41.8 (14.6)	48.8 (12.4)	0.058
SRS-22r							
Activity	2.6 (0.9)	3.1 (1.0)	2.4 (0.9)	0.016	2.7 (0.8)	2.5 (1.1)	0.130
Pain	2.1 (0.8)	2.5 (0.9)	2.0 (0.7)	0.039	2.1 (0.7)	2.2 (0.9)	0.694
Appearance	2.2 (0.7)	2.3 (0.7)	2.1 (0.8)	0.283	2.2 (0.8)	2.1 (0.7)	0.546
Mental	3.4 (0.9)	3.5 (1.0)	3.3 (0.9)	0.530	3.2 (0.9)	3.6 (0.9)	0.131
Satisfaction	2.6 (1.1)	2.7 (1.1)	2.5 (1.0)	0.620	2.4 (1.0)	2.8 (1.1)	0.090
Total	2.6 (0.7)	2.8 (0.8)	2.5 (0.6)	0.049	2.6 (0.6)	2.6 (0.7)	0.776
NRS score							
Back pain	7.0 (2.4)	6.6 (3.0)	7.1 (2.1)	0.774	6.7 (2.6)	7.3 (2.0)	0.582
Leg pain	4.8 (3.3)	3.9 (3.3)	5.1 (3.3)	0.206	4.7 (3.5)	4.9 (3.2)	0.958

CCI = Charlson Comorbidity Index; HTN = hypertension; Hx = history; PO = pelvic obliquity; TL = thoracolumbar.

Boldface type indicates statistical significance.

* Incomplete preoperative SVA data for 2 patients.

† Chi-square test, Fisher's exact test, independent-samples t-test, and Mann-Whitney U-test were performed.

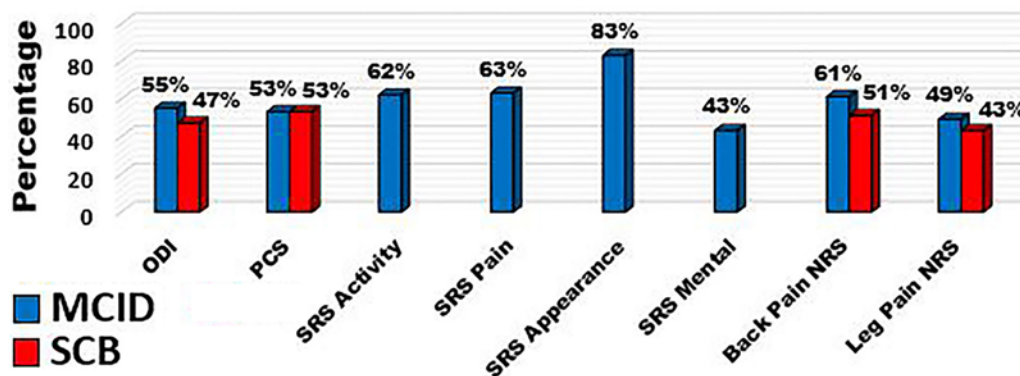


FIG. 1. Chart demonstrating the percentage of patients who reached an MCID and/or SCB after surgery. MCID and SCB were computed using HRQOL outcome measures at baseline and after 2 years' postoperative follow-up. NRS = NRS score. Figure is available in color online only.

Index Operation Data

Index operations are summarized in Table 2. The approach was either posterior only (58.1%) or anterior-posterior (41.9%). Most patients had an upper thoracic T2–5

(54.8%) or a lower thoracic T9–11 (38.7%) uppermost instrumented vertebra (UIV), 90.3% had iliac fixation, and the mean posterior fusion length was 13.2 levels. Smith-Petersen osteotomy, 3CO, and IBF were performed in 37

TABLE 2. Operative parameters for 62 adults with severe GCM surgically treated for spinal deformity with comparisons by baseline global malalignment

Variable	All Patients (n = 62)	Comparison by SVA*			Comparison by GCM		
		<10 cm (n = 20)	≥10 cm (n = 40)	p Value	<10 cm (n = 35)	≥10 cm (n = 27)	p Value
Pst procedure, no. (%)	62 (100)	—	—	—	—	—	—
Pst-only approach, no. (%)	36 (58.1)	45%	65%	0.139	51%	67%	0.228
Ant-pst approach, no. (%)	26 (41.9)	55%	35%	0.139	49%	33%	0.228
Pst levels fused (SD)	13.2 (3.8)	13.2 (3.5)	13.2 (4.0)	0.841	12.7 (3.9)	13.8 (3.6)	0.223
UIV location, no. (%)							
T2–5	34 (54.8)	50%	58%	0.582	49%	63%	0.259
T6–8	2 (3.2)	—	—	—	—	—	—
T9–11	24 (38.7)	40%	38%	0.851	43%	33%	0.445
Below T12	2 (3.2)	—	—	—	—	—	—
LIV location, no. (%)							
L5	2 (3.2)	—	—	—	—	—	—
Sacrum: S1, S2	4 (6.5)	—	—	—	—	—	—
Ilium	56 (90.3)	95%	88%	0.653	89%	93%	0.689
Decompression, no. (%)	42 (67.7)	60%	73%	0.326	71%	63%	0.480
Any osteotomy, no. (%)	50 (80.6)	75%	83%	0.511	77%	85%	0.427
SPO, no. (%)	37 (59.7)	55%	63%	0.576	57%	63%	0.643
No. of SPOs (SD)	5.1 (2.5)	2.7 (2.7)	3.3 (3.4)	0.553	3.0 (3.3)	3.1 (3.0)	0.831
3CO, no. (%)	22 (35.5)	25%	38%	0.333	29%	44%	0.195
No. of 3COs (SD)	1.0 (0)	0.3 (0.4)	0.4 (0.5)	0.337	0.3 (0.5)	0.4 (0.5)	0.199
IBF, no. (%)	45 (72.6)	70%	73%	0.839	77%	67%	0.359
No. of IBFs (SD)	2.9 (1.6)	2.8 (1.4)	3.0 (1.7)	0.849	3.1 (1.7)	2.5 (1.3)	0.273
Op time in hrs (SD)†	8.3 (3.0)	8.6 (3.7)	8.2 (2.7)	0.461	8.5 (2.6)	8.1 (3.4)	0.452
EBL in L (SD)†	2.3 (1.7)	1.9 (1.2)	2.4 (1.9)	0.239	2.0 (2.0)	2.5 (1.2)	0.020
ASD-surgical invasiveness score (SD)	121.3 (40.4)	107.0 (39.8)	128.7 (39.2)	0.049	119.6 (43.1)	123.6 (37.4)	0.707
LOS in days (SD)†	14.3 (10.6)	13.6 (11.4)	14.7 (10.5)	0.610	12.3 (7.2)	16.9 (13.5)	0.177

Ant = anterior; LIV = lowermost instrumented vertebra; LOS = length of hospital stay; pst = posterior; SPO = Smith-Petersen osteotomy.

Boldface type indicates statistical significance.

* Incomplete preoperative SVA data for 2 patients.

† Includes both anterior and posterior procedures, if applicable.

TABLE 3. Radiographic alignment after surgery

Radiographic Variable	Value at Last FU (SD)	Change From Baseline (SD)	p Value*
Coronal plane			
GCM in cm†	3.8 (2.8)	-6.8 (4.4)	<0.001
PO in °	2.5 (1.9)	-0.5 (2.6)	0.300
Upper thoracic in °	12.7 (10.5)	-2.4 (7.2)	0.110
Thoracic in °	12.0 (11.6)	-11.0 (11.9)	<0.001
TL in °	18.4 (12.3)	-19.5 (15.3)	<0.001
Lumbar in °	10.9 (8.8)	-19.4 (12.8)	<0.001
Max Cobb in °	19.9 (11.9)	-23.4 (14.2)	<0.001
Sagittal plane			
SVA in cm	3.8 (6.5)	-9.2 (6.4)	<0.001
PT in °	23.0 (10.1)	-5.6 (9.6)	<0.001
LL in °	48.1 (13.3)	+28.3 (18.2)	<0.001
PI in °	54.5 (11.4)	+0.3 (2.2)	0.216
PI-LL in °	5.1 (16.5)	-25.8 (17.8)	<0.001
TK in °	46.1 (14.1)	+15.3 (14.5)	<0.001

FU = follow-up.

Boldface type indicates statistical significance.

* Paired t-test or Wilcoxon signed-rank test of relationship between radiographic parameters at preoperative baseline and those at the last radiographic follow-up (mean 3.3 years).

† Absolute value.

TABLE 4. Partial correlations with postoperative HRQOL

Δ2Y HRQOL	Δ2Y SVA		Δ2Y GCM	
	r	p Value*	r	p Value†
ODI	-0.042	0.759	0.040	0.772
SF-36 PCS	-0.229	0.109	0.059	0.683
SF-36 MCS	-0.007	0.962	-0.019	0.898
SRS-22r				
Activity	-0.041	0.772	-0.187	0.180
Pain	-0.031	0.827	-0.097	0.491
Appearance	-0.001	0.992	-0.117	0.404
Mental	-0.128	0.362	-0.002	0.988
Satisfaction	0.196	0.164	0.012	0.930
Total	-0.013	0.925	-0.121	0.389
NRS score				
Back pain	0.209	0.126	0.077	0.574
Leg pain	0.151	0.270	-0.156	0.257

Δ2Y = 2-year change.

* Partial correlations between SVA and HRQOL 2-year postoperative changes, while controlling for changes in GCM.

† Partial correlations between GCM and HRQOL 2-year postoperative changes, while controlling for changes in SVA.

TABLE 5. HRQOL outcomes after surgery in 62 patients

HRQOL Measure	Last FU*	Baseline Change	p Value†
ODI	37 (23)	-14 (23)	<0.01
SF-36			
PCS	37 (10)	+8 (10)	<0.01
MCS	49 (12)	+4 (11)	<0.01
SRS-22r			
Activity	3.2 (0.9)	+0.6 (1.0)	<0.01
Pain	3.2 (1.1)	+1.0 (1.1)	<0.01
Appearance	3.5 (0.9)	+1.3 (0.9)	<0.01
Mental	3.7 (0.9)	+0.3 (0.8)	<0.01
Satisfaction	4.2 (1.0)	+1.7 (1.4)	<0.01
Total	3.5 (0.8)	+0.9 (0.7)	<0.01
NRS score			
Back pain	4.0 (3.2)	-2.9 (3.0)	<0.01
Leg pain	3.4 (3.0)	-1.4 (3.4)	<0.01

Values are presented as means (SD), unless indicated otherwise. Boldface type indicates statistical significance.

* Last clinical follow-up had a mean duration of 3.3 ± 1.1 years.

† Fisher's exact test, independent-samples t-test, and Mann-Whitney U-test were performed.

patients (59.7%; 5.1 per operation), 22 patients (35.5%; 1 per operation), and 45 patients (72.6%; 2.9 per operation), respectively. The mean operative duration was 8.3 ± 3.0 hours, and the mean estimated blood loss (EBL) was 2.3 ± 1.7 L. Most assessed operative parameters were comparable after subanalysis with 10-cm SVA and GCM cutoffs, except for EBL and ASD-surgical invasiveness score.¹⁶ A greater baseline GCM (≥ 10 cm) was associated with significantly higher EBL (2.5 vs 2.0 L, p = 0.020). A greater baseline SVA (≥ 10 cm) was associated with significantly more invasive operations based on ASD-surgical invasiveness scores (129 vs 107, p = 0.049).¹⁶ Controlling for GCM, ASD-surgical invasiveness correlated with initial SVA correction at 6 weeks (r = 0.582, p < 0.001). Controlling for SVA, ASD-surgical invasiveness did not correlate with initial GCM correction at 6 weeks (r = 0.056, p = 0.674).

Radiographic Correction, Partial Correlations, and Linear Regression for HRQOL

Radiographic measurements at the last follow-up (mean 3.3 ± 1.1 years) are summarized in Table 3 and include GCM = 3.8 ± 2.8 cm (-6.8 cm change, p < 0.001), thoracic Cobb = 12.0° ± 11.6° (-11.0° change, p < 0.001), thoracolumbar Cobb = 18.4° ± 12.3° (-19.5° change, p < 0.001), lumbar Cobb = 10.9° ± 8.8° (-19.4° change, p < 0.001), SVA = 3.8 ± 6.5 cm (-9.2 cm change, p < 0.001), PT = 23.0° ± 10.1° (-5.6° change, p < 0.001), LL = 48.1° ± 13.3° (+28.3° change, p < 0.001), and PI-LL = 5.1° ± 16.5° (-26° change, p < 0.001). No significant partial correlations were demonstrated between 2-year postoperative HRQOL changes and GCM or SVA corrections (Table 4). Linear regression analysis demonstrated that GCM and SVA correction were not significant predictors of 2-year HRQOL changes (Supplemental Table

TABLE 6. Percentage of patients reaching ≥ 1 MCID/SCB improvement with comparisons by baseline SVA and GCM

$\Delta 2Y$ HRQOL*	Among All Patients at 2-Yr FU	Comparison by SVA†			Comparison by GCM		
		<10 cm (n = 20)	≥ 10 cm (n = 40)	p Value‡	<10 cm (n = 35)	≥ 10 cm (n = 27)	p Value‡
ODI		-17 (16)	-19 (20)	0.81	-21 (20)	-15 (17)	0.27
MCID	55%	55%	55%	1.00	57%	52%	0.78
SCB	47%	50%	45%	0.86	54%	37%	0.20
PCS		+5 (10)	+9 (12)	0.24	+8 (11)	+8 (12)	0.96
MCID	53%	56%	49%	0.23	46%	63%	0.03
SCB	53%	56%	49%	0.23	46%	63%	0.03
MCS		+7 (9)	+3 (9)	0.07	+6 (9)	+1 (9)	0.09
SRS-22r							
Activity		+0.5 (0.5)	+0.7 (1.0)	0.71	+0.6 (0.9)	+0.6 (0.7)	0.83
MCID	62%	61%	63%	0.16	59%	65%	0.86
Pain		+0.9 (1.2)	+1.1 (1.1)	0.61	+1.2 (1.2)	+0.8 (1.0)	0.13
MCID	63%	67%	63%	0.79	68%	58%	0.79
Appearance		+1.5 (0.7)	+1.3 (1.0)	0.58	+1.4 (0.8)	+1.4 (1.0)	0.98
MCID	83%	94%	78%	0.39	85%	81%	0.86
Mental		+0.3 (0.9)	+0.4 (0.7)	0.79	+0.5 (0.7)	+0.2 (0.9)	0.46
MCID	43%	39%	48%	0.82	44%	42%	1.00
Satisfaction		+1.7 (1.5)	+1.5 (1.3)	0.64	+2.0 (1.3)	+1.1 (1.3)	0.02
Total		+0.9 (0.6)	+0.9 (0.7)	0.66	+1.0 (0.7)	+0.8 (0.7)	0.25
NRS							
Back pain		-2.1 (3.4)	-3.2 (3.1)	0.20	-2.4 (3.5)	-3.3 (2.8)	0.29
MCID	61%	47%	65%	0.41	50%	74%	0.17
SCB	51%	58%	50%	0.80	53%	48%	0.76
Leg pain		-1.0 (5.2)	-2.0 (3.2)	0.41	-1.6 (4.3)	-1.8 (3.3)	0.84
MCID	49%	47%	50%	<0.05	44%	56%	0.65
SCB	43%	42%	43%	0.15	44%	41%	0.81

Boldface type indicates statistical significance. Values presented as means (SD) or percent, unless indicated otherwise.

* Postoperative HRQOL changes and percentage of patients reaching ≥ 1 MCID/SCB improvement were assessed at the 2-year follow-up.

† Incomplete preoperative SVA data for 2 patients.

‡ Fisher's exact test, independent-samples t-test, and Mann-Whitney U-test were performed.

2). Final global alignment correction was 65% and 71% for GCM and SVA, respectively.

HRQOL Outcomes and Attaining Thresholds of Improvement for MCID and SCB

HRQOL outcomes after surgery and patients reaching ≥ 1 MCID/SCB improvement are summarized in Tables 5 and 6. All assessed HRQOL measures were significantly improved at the last follow-up (mean 3.3 ± 1.1 years) compared to baseline ($p < 0.01$): ODI, 51 to 37; PCS, 29 to 37; SRS-22r Total, 2.6 to 3.5; and NRS back and leg pain, 7 to 4 and 5 to 3, respectively. Thresholds for ≥ 1 MCID/SCB improvement were achieved in 43%–83% of patients at the 2-year follow-up. The highest percentage of patients who reached a 2-year MCID/SCB improvement was 83% for SRS-22r Appearance (MCID) and 53% for PCS (SCB; Fig. 1). Postoperative 2-year HRQOL changes and percentages reaching ≥ 1 MCID/SCB were subanalyzed by severity of baseline SVA and GCM with 10-cm cutoffs (Table 6). Comparisons by SVA demonstrated a significant difference in NRS leg pain scores ($p < 0.05$). Comparisons by GCM demonstrated significant differences in

PCS MCID/SCB ($p = 0.03$) and SRS-22r Satisfaction ($p = 0.02$).

Complications Associated With Surgery

Table 7 summarizes types and rates of complications associated with surgery. A total of 89 complications were reported (34 minor, 55 major), and 45 (73%) patients had ≥ 1 complication. Overall, the complications with the highest rates were rod fracture (19%, occurring at T12–L1 to L5–S1 except L1–2), proximal junctional kyphosis (PJK; 18%), and durotomy (15%). There were 34 reoperations in 22 (35%) patients with the most common indications of PJK ($n = 6$), rod fracture ($n = 5$), coronal imbalance ($n = 4$), and deep wound infection ($n = 4$). The 18 patients who did not have a 2-year follow-up had a mean follow-up of 0.63 years, and the general distribution and types of complications encountered in these 18 patients were comparable to the complication data for patients with a 2-year follow-up; there were 18 total complications (8 minor, 10 major), 11 (61.1%) patients had ≥ 1 complication, and 2 reoperations were performed for screw fracture and pseudarthrosis (Table 8).

TABLE 7. Type and rates of complications in 62 adults with severe GCM surgically treated for spinal deformity and a minimum 2-year follow-up

Complication Category	Minor/Major Complication (%), No. of Reops			
	Intraop	Early (≤30 days)	Delayed (>30 days)	Total
Implant	0/0 (0)	0/0 (0)	3/15 (29.0), 8	3/15 (29.0), 8
Rod breakage	0/0 (0)	0/0 (0)	1/11 (19.4), 5	1/11 (19.4), 5
Painful implant	0/0 (0)	0/0 (0)	1/2 (4.8), 2	1/2 (4.8), 2
Screw medial breach	0/0 (0)	0/0 (0)	0/2 (3.2), 1	0/2 (3.2), 1
Implant prominence	0/0 (0)	0/0 (0)	1/0 (1.6)	1/0 (1.6)
Radiographic	0/0 (0)	1/0 (1.6)	4/17 (33.9), 15	5/17 (35.5), 15
PJK	0/0 (0)	1/0 (1.6)	3/7 (16.1), 6	4/7 (17.7), 6
Coronal imbalance	0/0 (0)	0/0 (0)	0/4 (6.5), 4	0/4 (6.5), 4
Pseudarthrosis	0/0 (0)	0/0 (0)	0/4 (6.5), 3	0/4 (6.5), 3
Adjacent-segment disease	0/0 (0)	0/0 (0)	1/1 (3.2), 1	1/1 (3.2), 1
Sagittal imbalance	0/0 (0)	0/0 (0)	0/1 (1.6), 1	0/1 (1.6), 1
Neurological	1/1 (3.2), 1	1/1 (3.2)	2/6 (12.9), 2	4/8 (19.4), 3
Motor deficit	0/1 (1.6), 1	0/0 (0)	0/4 (6.5)	0/5 (8.1), 1
Radiculopathy	0/0 (0)	1/1 (3.2)	2/1 (4.8), 1	3/2 (8.1), 1
Mental status change	1/0 (1.6)	0/0 (0)	0/0 (0)	1/0 (1.6)
Myelopathy	0/0 (0)	0/0 (0)	0/1 (1.6), 1	0/1 (1.6), 1
Op	9/7 (25.8), 2	1/2 (4.8), 1	0/0 (0)	10/9 (30.6), 3
Dural tear	9/0 (14.5)	0/0 (0)	0/0 (0)	9/0 (14.5)
Excessive blood loss	0/3 (4.8)	0/0 (0)	0/0 (0)	0/3 (4.8)
Vascular injury	0/2 (3.2)	0/1 (1.6), 1	0/0 (0)	0/3 (4.8), 1
Positioning	0/1 (1.6), 1	0/0 (0)	0/0 (0)	0/1 (1.6), 1
Pleural injury	0/0 (0)	1/0 (1.6)	0/0 (0)	1/0 (1.6)
Monitoring anomaly	0/1 (1.6), 1	0/0 (0)	0/0 (0)	0/1 (1.6), 1
Lymphocele	0/0 (0)	0/1 (1.6)	0/0 (0)	0/1 (1.6)
Cardiopulmonary	1/1 (3.2), 1	0/3 (4.8)	0/1 (1.6)	1/5 (9.7), 1
Pulmonary embolism	0/0 (0)	0/2 (3.2)	0/0 (0)	0/2 (3.2)
Deep vein thrombosis	0/0 (0)	0/0 (0)	0/1 (1.6)	0/1 (1.6)
Myocardial infarction	0/0 (0)	0/1 (1.6)	0/0 (0)	0/1 (1.6)
Tachyarrhythmia	0/1 (1.6), 1	0/0 (0)	0/0 (0)	0/1 (1.6), 1
Pleural effusion	1/0 (1.6)	0/0 (0)	0/0 (0)	1/0 (1.6)
Infection	0/0 (0)	1/1 (3.2), 1	3/0 (4.8), 3	4/1 (8.1), 4
Deep wound infection	0/0 (0)	0/1 (1.6), 1*	0/0 (0), 3*	0/1 (1.6), 4*
Urinary tract infection	0/0 (0)	1/0 (1.6)	3/0 (4.8)	4/0 (6.5)
GI	1/0 (1.6)	5/0 (8.1)	1/0 (1.6)	7/0 (11.3)
Ileus	1/0 (1.6)	3/0 (4.8)	1/0 (1.6)	5/0 (8.1)
GI bleed	0/0 (0)	1/0 (1.6)	0/0 (0)	1/0 (1.6)
Cholecystitis	0/0 (0)	1/0 (1.6)	0/0 (0)	1/0 (1.6)
Death	0/0 (0)	0/0 (0)	0/0 (0)	0/0 (0)
Total no. of complications (minor/major), no. of reops	21 (12/9), 4	16 (9/7), 2	52 (13/39), 28	89 (34/55), 34
No. of patients affected (%)	15 (24.2)	12 (19.4)	33 (53.2)	45 (72.6)

GI = gastrointestinal.

The number of reoperations associated with this complication category or the subset of major complications associated with the need for revision.

* One patient underwent 4 reoperations for deep wound infection.

Predictors of Minimal Disability (ODI ≤ 20), Residual GCM ≥ 3 cm, and Major Complications

Binary logistic regression was performed to identify predictors of minimal disability (ODI ≤ 20). Significant

univariate predictors of ODI ≤ 20 at the final follow-up included no prior spine surgery (p = 0.04), lower baseline SVA (p < 0.05), lower baseline ODI (p < 0.01), and lower baseline NRS leg pain score (p < 0.01). These variables

TABLE 8. Complications associated with ASD surgery in 18 patients with severe GCM who did not have a 2-year follow-up

Complication Category	Minor/Major Complication (% of total), No. of Reops			Total
	Intraop	Early (≤30 days)	Delayed (>30 days)	
Op	3/2 (27.8)	0/0 (0)	0/0 (0)	3/2 (27.8)
Dural tear	3/0 (16.7)	0/0 (0)	0/0 (0)	3/0 (16.7)
Excessive blood loss	0/2 (11.1)	0/0 (0)	0/0 (0)	0/2 (11.1)
Infection	0/0 (0)	0/0 (0)	1/2 (16.7)	1/2 (16.7)
Pneumonia	0/0 (0)	0/0 (0)	0/1 (5.6)	0/1 (5.6)
Urinary tract infection	0/0 (0)	0/0 (0)	0/1 (5.6)	0/1 (5.6)
Superficial	0/0 (0)	0/0 (0)	1/0 (5.6)	1/0 (5.6)
Implant	0/0 (0)	0/0 (0)	0/2 (11.1), 1	0/2 (11.1), 1
Rod breakage	0/0 (0)	0/0 (0)	0/1 (5.6)	0/1 (5.6)
Screw fracture	0/0 (0)	0/0 (0)	0/1 (5.6), 1	0/1 (5.6), 1
Radiographic	0/0 (0)	0/0 (0)	1/1 (11.1), 1	1/1 (11.1), 1
PJK	0/0 (0)	0/0 (0)	1/0 (5.6)	1/0 (5.6)
Pseudarthrosis	0/0 (0)	0/0 (0)	0/1 (5.6), 1	0/1 (5.6), 1
Neurological: motor deficit	0/2 (11.1)	0/0 (0)	0/0 (0)	0/2 (11.1)
Cardiopulmonary	0/0 (0)	1/1 (11.1)	0/0 (0)	1/1 (11.1)
Other	0/0 (0)	1/0 (5.6)	0/0 (0)	1/0 (5.6)
Pleural effusion	0/0 (0)	0/1 (5.6)	0/0 (0)	0/1 (5.6)
GI: ileus	0/0 (0)	1/0 (5.6)	1/0 (5.6)	2/0 (11.1)
Death	0/0 (0)	0/0 (0)	0/0 (0)	0/0 (0)
Total no. of complications (minor/major), no. of reops	7 (3/4), 0	3 (2/1), 0	8 (3/5), 2	18 (8/10), 2
No. of patients affected (%)	5 (27.8)	3 (16.7)	6 (33.3)	11 (61.1)

The number of reoperations associated with this complication category or the subset of major complications associated with the need for revision.

were no longer significant after multivariate analysis (Table 9).

Using 1-mm increments, iterative univariate analyses of all HRQOL instruments demonstrated GCM ≥ 3 cm as a potential residual threshold magnitude of coronal offset associated with significantly worse HRQOL (Supplemental Fig. 2). At the last follow-up, patients (n = 32) with residual GCM ≥ 3 cm had significantly worse SRS-22r Appearance and Satisfaction than the patients (n = 30) with a final GCM < 3 cm (3.3 ± 0.8 vs 3.7 ± 0.8 , p = 0.04; and 4.0 ± 1.0 vs 4.4 ± 0.9 , p = 0.02, respectively). All other HRQOL assessments were comparable. Further subanalysis of patients (n = 37) with adequate SVA correction (SVA < 5 cm) demonstrated that the patients (n = 17) with residual GCM ≥ 3 cm still had significantly worse SRS-22r Appearance and Satisfaction than the patients (n = 20) with a final GCM < 3 cm (3.3 ± 0.7 vs 3.9 ± 0.8 , p = 0.03; and 3.8 ± 1.0 vs 4.5 ± 0.9 , p < 0.01, respectively). No significant baseline

or perioperative predictors were identified for postoperative residual GCM ≥ 3 cm (Table 9).

No significant baseline or perioperative predictors, including 3CO, were identified for the occurrence of a major complication (Table 9).

Discussion

Early ASD studies provided limited evidence that suggested substantial GCM may negatively impact HRQOL.^{1,7} In 2005, Glassman et al. reported that GCM > 4 cm was associated with worse pain and function for unoperated ASD patients.¹ However, in the same study, the authors reported sagittal correction as the most critical goal of surgery but acknowledged the limited size of their severe-GCM subgroup (n = 11) and the nonsignificant trend toward worse Self-Image in these patients.¹ Later in 2009, Ploumis et al. reported that GCM > 5 cm had a significant negative impact on physical function in 58 symptomatic degenerative adult scoliosis patients.⁷ Others also suggested the deterioration of HRQOL in patients with a more severe GCM > 4 cm but provided limited supporting evidence.³²

Since then, there has been substantial research focused on sagittal radiographic analysis of ASD, which has led to well-defined age-adjusted sagittal correction goals.^{1-5,33} In comparison, less progress has been made for coronal plane assessment, and coronal correction thresholds for optimizing clinical outcomes remain unclear. In addition, the global coronal balance modifier previously considered in the 2006 SRS classification was removed in subsequent classifications.^{22,34} However, neglecting GCM may lead to suboptimal outcomes, and some have suggested that the clinical impact of this global parameter may be underestimated.^{8,14}

Prior coronal ASD studies often involved patients with a lower mean GCM, which potentially limited the likelihood of detecting impactful GCM and HRQOL associations.^{1,32,35} Therefore, in the current study, we included only patients with more substantial GCM, which we defined as ≥ 1 SD above the mean using a large multicenter, prospectively collected operative cohort (n = 691). We identified 62 index operative cases with a severe baseline GCM ≥ 7 cm and minimum 2-year follow-up. The cohort's mean GCM of 10.5 ± 3.6 cm would likely be considered quite substantial by most deformity surgeons and, to our knowledge, may represent the largest average global coronal offset in the contemporary ASD surgical literature. Nonoperative patients were not included in the current study since they may be less severely impacted by spinal deformity, hence obviating the need to pursue surgical treatment.³⁶⁻³⁸

At baseline, the study cohort was considered frail,¹⁵ roughly half (57%) had undergone prior spine surgery, and the majority (87%) had ≥ 1 comorbidity, with hypertension (45%) and depression (32%) most commonly reported. On average, the cohort reported severe disability (mean ODI = 51.0 ± 20.1), severe back pain (NRS score = 7.0 ± 2.4), and moderate leg pain (NRS score = 4.8 ± 3.3). Concurrent severe sagittal deformity was highly prevalent, with the majority (81%) of patients characterized by ≥ 1 severe sagittal spinopelvic modifier per the SRS-Schwab classification.²² This is consistent with other studies reporting

TABLE 9. Baseline and perioperative factors that predict minimal disability (ODI ≤ 20), residual GCM ≥ 3 cm, and major complication occurrence

Variable	Predictor of ODI ≤ 20			Predictor of Residual GCM ≥ 3 cm			Predictor of Major Compl		
	ODI ≤ 20 (n = 15)	ODI > 20 (n = 47)	p Value*	GCM ≥ 3 cm (n = 32)	GCM < 3 cm (n = 30)	p Value*	Major Compl (n = 15)	No Major Compl (n = 47)	p Value*
Baseline									
Age in yrs (SD)	64 (7)	64 (12)	0.86	65 (11)	63 (11)	0.63	65 (8)	63 (11)	0.48
Female sex (%)	80%	81%	1.0	78%	83%	0.60	80%	81%	1.0
BMI in kg/m ² (SD)	25 (5)	28 (6)	0.19	27 (7)	27 (6)	0.83	26 (7)	27 (6)	0.48
CCI (SD)	1.3 (1.0)	2.3 (1.8)	0.07	2.1 (1.8)	2.1 (1.6)	0.63	2.2 (1.5)	2.1 (1.8)	0.60
Osteopor (%)	27%	26%	1.0	31%	20%	0.31	20%	28%	0.74
Prior spine surgery (%)	33%	64%	0.04	56%	57%	0.97	47%	60%	0.38
			(0.61–8.39)						
GCM in cm (SD)	10 (3)	11 (4)	0.84	11 (3)	10 (4)	0.19	11 (3)	10 (4)	0.52
									(1.00–1.03)
Max coronal Cobb in ° (SD)	51 (14)	41 (20)	0.09	43 (19)	44 (19)	0.96	42 (14)	44 (20)	0.67
C7-SVA in cm (SD)	10 (6)	14 (7)	<0.05	13 (8)	12 (7)	0.61	14 (8)	13 (7)	0.56
			(0.99–1.01)						
PT in ° (SD)	27 (9)	29 (12)	0.31	30 (9)	27 (13)	0.27	28 (11)	29 (11)	0.70
									(1.00–1.12)
PI-LL in ° (SD)	25 (18)	33 (21)	0.22	33 (21)	28 (20)	0.35	32 (23)	31 (20)	0.79
ODI (SD)	33 (21)	57 (16)	<0.01	51 (22)	51 (18)	0.63	57 (17)	49 (21)	0.13
			(0.98–1.06)						(0.98–1.05)
NRS back pain (SD)	6 (2)	7 (2)	0.23	7 (2)	7 (2)	0.46	7 (2)	7 (2)	0.59
NRS leg pain (SD)	3 (3)	5 (3)	<0.01	5 (3)	5 (4)	0.65	6 (3)	4 (3)	0.27
			(0.92–1.41)						(0.88–1.32)
Op									
Pst levels fused, no. (SD)	13 (5)	13 (4)	0.99	13 (4)	13 (4)	0.77	13 (3)	13 (4)	0.32
3CO (%)	27%	38%	0.41	41%	30%	0.38	27%	38%	0.41
IBF (%)	87%	68%	0.20	75%	70%	0.66	80%	70%	0.53
Op time in mins (SD)	488 (253)	504 (153)	0.56	522 (210)	476 (142)	0.30	577 (182)	475 (174)	0.08
									(0.998–1.004)
EBL in L (SD)	2.0 (1.2)	2.3 (1.8)	0.45	2.2 (1.2)	2.3 (2.1)	0.67	2.9 (2.9)	2.1 (1.0)	0.81
Major compl (%)	20%	26%	1.0	53%	51%	0.88			
Any compl (%)	60%	77%	0.32	56%	41%	0.31			

Compl = complication; osteopor = osteoporosis.

Boldface type indicates statistical significance.

* Univariate comparisons with independent-samples t-test, Mann-Whitney U-test, Fisher's exact test, and chi-square test were performed.

† Univariate predictors with p < 0.05 were included in binary logistic regression analysis.

‡ Univariate predictors with p ≤ 0.30 were included in binary logistic regression analysis.

a frequent association of severe coronal deformity with sagittal malalignment.³⁵ In fact, we also found a positive correlation between baseline GCM and SVA ($r = 0.313$, $p = 0.015$).

At baseline, univariate analysis demonstrated significant association between increased sagittal imbalance (SVA ≥ 10 cm) and worse HRQOL (ODI, PCS, and SRS-22r Activity, Pain, and Total). All HRQOL measures were comparable between severe GCM (7–10 cm) and very severe GCM (≥ 10 cm) subgroups; however, there was a trend toward a worse physical health status in the patients with very severe GCM. Collectively, these results suggest that prior to surgical treatment, severe GCM patients often have concurrent severe global sagittal malalignment, which seems to be the significant driver for worse HRQOL.

Surgical correction of severe ASD often entails complex reconstruction with long-segment posterior fusion, multiple osteotomies, and pelvic fixation.³⁹ This description accurately characterizes the operations in this study, with over a third (36%) of patients undergoing 3CO, a mean of 13.2 ± 3.8 fused levels, upper thoracic (T2–5) UIV in 55% of patients, lower thoracic (T9–11) UIV in 39%, and iliac fixation in 90%. Increased sagittal malalignment (SVA ≥ 10 cm) was significantly associated with higher ASD-surgical invasiveness.¹⁶ Also, there was a positive correlation between ASD-surgical invasiveness and SVA correction, but not with GCM correction. This is likely because ASD-surgical invasiveness does not consider C7–S1 global coronal offset.¹⁶ Thus, this scoring system may underestimate the impact of GCM correction on surgical duration and blood loss, especially given that the current study results demonstrated significantly higher EBL in patients with more severe baseline GCM.

Surgery resulted in a mean GCM correction of 65% (10.5 to 3.8 cm) in this study. Limited literature is available for comparison since GCM is infrequently specified in other ASD surgical reports. Also, as mentioned above, the few studies that have focused on surgical GCM correction involved patients with less severe coronal offsets.^{35,40} Bradford and Tribus described 24 patients (mean age 27 years) with rigid coronal decompensation (mean GCM 8.5 cm) and reported 82% GCM correction using anterior-posterior vertebral column resection.⁴⁰ In a different study, Daubs et al. reported 42% GCM correction in 85 adults with a minimum GCM of 4 cm (mean 6.2 ± 2.3 cm).³⁵ The authors reported that GCM improvement trended toward, but was not a significant predictor of, improved ODI.³⁵ They also suggested a potential minimum GCM (i.e., > 10 cm) whereby correction may predict postoperative functional outcomes, but acknowledged that their study cohort had patients with insufficient GCM magnitudes for more rigorous statistical analysis.³⁵

In the current study, surgery was associated with significant improvement in all HRQOL measures at the last follow-up. Furthermore, we identified a postoperative residual GCM threshold of 3 cm that was associated with significantly worse HRQOL (SRS-22r Appearance and Satisfaction); this was redemonstrated even in the subset of patients with appropriate sagittal realignment. Previous authors have also described the impact of substantial GCM and its correction on Appearance/Self-Image.^{1,12}

Lewis et al. found that postoperative coronally balanced patients (mean GCM 1.3 cm) had significantly greater improvement in SRS-22r Appearance than imbalanced patients (mean GCM 4.8 cm).¹² The authors found comparable HRQOL scores in all other assessed SRS-22r subdomains.¹² Collectively, these results suggest that surgical correction of severe GCM significantly impacts HRQOL and that SRS-22r Appearance seems to be negatively affected when appropriate restoration of GCM is not achieved. We identified 3 cm as a potential target coronal realignment threshold and recommend that surgeons correct severe GCM within this threshold to optimize clinical outcomes and patient satisfaction. However, we acknowledge that this threshold may not be generalizable to all GCM patients, especially those with “mild” or “moderate” GCM.

MCID/SCB improvements were achieved in 43%–83% (highest MCID and SCB for SRS-22r Appearance [83%] and PCS [53%], respectively). The percentage of patients reaching ≥ 1 MCID improvement was similar to those reported in other multicenter ASD outcome studies.⁴¹ Notably, MCID improvement for an operative cohort ($n = 286$) reported by Smith et al. was as follows: ODI, 53%; PCS, 59%; SRS-22r Activity, 61%; SRS-22r Pain, 66%; SRS-22r Appearance, 73%; SRS-22r Mental, 41%; NRS back pain, 71%; and NRS leg pain, 44%.⁴¹ In comparison to the current study, the largest difference in MCID improvement was demonstrated in the SRS-22r Appearance subdomain (83% achieved ≥ 1 MCID). These results further support the potential association between surgical correction of severe GCM and the Appearance/Self-Image subdomain.

Severe GCM is frequently associated with severe sagittal spinopelvic malalignment.^{10,35} As previously discussed, this applied to the majority (81%) of our cohort.²² Thus, we thought it important to investigate the impact of sagittal versus coronal correction on clinical outcomes. Although the current analysis did not reveal significant partial correlations between HRQOL improvement and GCM/SVA correction, subanalyzing patients based on 10-cm SVA/GCM cutoffs produced statistically significant results. A significantly greater percentage of patients with worse baseline GCM (≥ 10 cm) attained MCID/SCB improvement for PCS at the 2-year follow-up. However, the same subgroup with worse baseline GCM demonstrated significantly less improvement in SRS-22r Satisfaction. This suggests that more severe GCM patients may have a greater chance of clinically meaningful physical health improvement after surgery; however, they may still have less treatment satisfaction than their less severely imbalanced counterparts.

In the current study, most (73%) patients reported ≥ 1 complication (89 total, 34 minor, 55 major), 24% of which were intraoperative, 19% early (≤ 30 days postoperative), and 53% delayed (> 30 days postoperative). These rates are high compared to those in a review by Sciubba et al., which reported mean overall and long-term deformity surgery complication rates of 55% and 21%, respectively.⁴² The review by Sciubba et al. comprised 93 articles with thousands of patients;⁴² therefore, our smaller study cohort could potentially account for some differences in reported complication rates. However, the higher com-

plication rates in the current study are similar to those in other recent multicenter ASD surgical reports and may be related to the substantial baseline global deformity present in this cohort, the high rate of 3CO performed, and patient frailty.^{15,17,18} Rod fracture and PJK were the most common complications and indications for reoperations (34 reoperations in 22 [35%] patients). Possible strategies to reduce rod fractures and PJK include the use of accessory rods and tethers, respectively.^{43–45}

A minimum 2-year follow-up was completed by 78% of patients in the current study. The reasons the remaining 18 patients did not have a 2-year follow-up are unknown. To assess whether the occurrence of complications could be a factor in their shorter follow-up, complications for these 18 patients were separately assessed. We found that 11 (61%) of these patients had ≥ 1 complication and that there were 2 reoperations; therefore, there does not appear to be a disproportionate rate of complications that could potentially explain a lack of follow-up in this study.

The strengths of this study include its multicenter prospective methodology and thorough assessment of patient-reported outcomes and complications using standardized collection forms, onsite study coordinators, and regular centralized data auditing. The multicenter design with 13 different sites across the United States allows for better generalizability of study results. Also, to our knowledge, this study represents the largest multicenter operative ASD cohort with a substantially larger mean GCM than previously analyzed. The substantial baseline GCM allowed rigorous and focused investigation, which was likely not possible in prior studies limited by less severe GCM, and initial progress was made toward establishing optimal target coronal alignment thresholds. The results of this study provide the most complete assessment of surgical outcomes for severe GCM correction, and we report benchmark complication rates to guide spine surgeons and facilitate the patient counseling process.

Study limitations include the arbitrary definition of “severe” GCM represented as ≥ 1 SD above the mean. We acknowledge that this mathematical definition may fail to capture all clinically relevant cases of severe GCM and that further investigations may be needed to elucidate possible threshold magnitudes of GCM that are mild, moderate, or severe. However, we think most deformity surgeons would consider a minimum coronal offset of 7 cm to be severe; therefore, the current study results are likely still applicable. Also, we acknowledge that sagittal correction is a potential confounder when interpreting these results; however, excluding baseline sagittal malaligned patients would be difficult given that severe GCM typically coexists with sagittal deformity. Another study limitation is that multivariate modeling failed to identify significant predictors of attaining an ODI ≤ 20 (minimal disability), predictors of postoperative residual GCM ≥ 3 cm, and predictors for the occurrence of major complications. Despite the lack of significant multivariate results on secondary subanalysis, we think the primary objective of assessing surgical outcomes and complications in severe GCM patients was still achieved. Finally, although we provide evidence to suggest 3 cm as a potential surgical GCM correction threshold, we acknowledge these results were based on the assessment of

62 patients and may not be generalizable to a larger cohort with less severe GCM.

Conclusions

This study provides a multicenter assessment of treatment outcomes and complications associated with ASD surgery in severe GCM patients (≥ 7 cm, mean 10.5 ± 3.6 cm) with a minimum 2-year follow-up (mean clinical follow-up 3.3 ± 1.1 years). At baseline, patients were frail, and most had concurrent severe sagittal spinopelvic deformity and reported severe pain and disability. Operations were complex and many (36%) involved 3COs. Surgery was associated with significant biplane alignment correction (65% GCM, 71% SVA) and HRQOL improvement despite high complication rates (rod fracture and PJK as the most common). MCID improvement was highest for SRS-22r Appearance/Self-Image (83%). Residual GCM ≥ 3 cm was associated with a worse outcome, even in patients with appropriate sagittal realignment, which suggests a potential target coronal realignment threshold to assist surgical planning. These results likely represent initial progress toward establishing coronal correction goals; however, further investigation is needed to assess their validity for mild or moderate GCM. To our knowledge, this study is the most complete and detailed report of surgical outcomes and complications for a large ASD cohort with a substantially larger GCM than previously analyzed. These findings may prove useful as renewed focus is directed toward coronal plane analysis and elucidating the potentially underestimated impact of GCM.

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Supplemental Information

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