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Prevalence and Prognosis of Coronal Malalignment Following Lateral Lumbar Interbody Fusion for Minimally Invasive Treatment of Adult Spinal Deformity

Andrew K. Chan, M.D[1]., Shailen G. Sampath, M.Sc.[1], Praveen V. Mummaneni, M.D., M.B.A.[2], Paul Park M.D.[3], Juan S. Uribe, M.D.[4], Jay D. Turner M.D., Ph.D.[4], Vivian P. Le, M.P.H.[1], Robert K. Eastlack, M.D.[5], Richard G. Fessler, M.D., Ph.D.[6], Khoi D. Than, M.D.[7], Kai-Ming Fu, M.D., Ph.D.[3], Michael Y. Wang, M.D.[8], Adam S. Kanter, M.D.[9], David O. Okonkwo, M.D., Ph.D.[9], Pierce D. Nunley, M.D.[10], Neel Anand, M.D.[11], Gregory M. Mundis, Jr., M.D.[5], Peter G. Passias, M.D.[12], Shay Bess M.D.[13], Christopher I. Shaffrey, M.D.[7], Dean Chou, M.D.[1], and the International Spine Study Group

[1]Department of Neurological Surgery, Columbia University, New York, NY, USA

[2]Department of Neurological Surgery, University of California, San Francisco, CA, USA

[3]Department of Neurological Surgery, University of Tennessee; Semmes-Murphey Neurologic and Spine Institute, Memphis, TN, USA

[4]Department of Neurosurgery, Barrow Neurological Institute, Phoenix, AZ, USA

[5]Division of Orthopaedic Surgery, Scripps Clinic, La Jolla, CA, USA

[6]Department of Neurosurgery, Rush University Medical Center, Chicago, IL, USA

[7]Department of Neurosurgery, Duke University Medical Center, Durham, NC, USA

[8]Department of Neurological Surgery, Weill Cornell Medical Center, New York, NY, USA

[9]Department of Neurological Surgery, University of Miami, Miami, FL, USA

[10]Department of Neurosurgery, Hoag Pickup Family Neurosciences Institute, Newport Beach, CA

[11]Department of Neurological Surgery, University of Pittsburgh Medical Center, Pittsburgh, PA, USA

[12]Department of Orthopedic Surgery, Spine Institute of Louisiana, Shreveport, LA, USA

[13]Department of Orthopedic Surgery, Cedars-Sinai Health Center, Los Angeles, CA, USA

[14]Departments of Orthopedic and Neurological Surgery, NYU Langone Orthopedic Hospital; New York Spine Institute, New York, NY, USA

Department of Neurosurgery, Duke University Medical Center, Durham, NC, USA

[15]Department of Spine Surgery, Denver International Spine Center, Presbyterian St. Luke's/Rocky Mountain Hospital for Children, Denver, CO, USA

[16] Departments of Neurological Surgery and Orthopedic Surgery, Duke University; Durham, NC, USA

Corresponding Author

Andrew K. Chan, MD

Department of Neurological Surgery

Columbia University Vagelos College of Physicians and Surgeons

The Och Spine Hospital at NewYork-Presbyterian

5141 Broadway, 3FW, Room 20, New York, NY 10034

akc2136@columbia.edu

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ABSTRACT

STUDY DESIGN: Retrospective analysis of prospective multicenter adult spinal deformity (ASD) database.

OBJECTIVE: To determine the prevalence and prognosis of postoperative coronal malalignment following LLIF for ASD with Qiu type A coronal alignment.

SUMMARY OF BACKGROUND DATA: Qiu Type A coronal alignment is defined as coronal vertical axis (CVA) <30mm.[1] There is concern that circumferential minimally invasive surgery (cMIS) with lateral lumbar interbody fusion (LLIF) is associated with postoperative coronal malalignment in ASD with preoperative Qiu type A patients.

METHODS: Qui type A patients undergoing cMIS with LLIF for ASD were included, with ASD defined with at least: maximum CC≥20°, SVA>5 cm, PI-LL≥10°, or PT>20°. Two year

(2Y) clinical outcomes were compared for type A with 2Y CVA≥30 mm (MAL) versus <30 mm (ALIGN) and were adjusted for factors reaching $p<0.05$ on univariate comparisons (age, BMI, and ODI).

RESULTS: 43 patients met inclusion criteria, of which 12 (27.9%) developed coronal malalignment and 31 (72.1%) remained coronally aligned at 2Y. At baseline, MAL were older (73.0 vs. 69.0, p=0.045), had a lower BMI (26.09 vs. 29.45, p=0.047), and were less disabled (ODI 42.83 vs. 51.69, p=0.016). Otherwise, the groups were well-matched for baseline characteristics. At 2Y, MAL had a greater 2Y SVA (mean 54.08 vs 19.00 mm, p=0.01). Clinically, MAL was associated with inferior 2Y SF-36 PCS (34.78 vs. 37.42, adj p=0.043) and 2Y SRS-22r function/activity domain (3.03 vs. 3.36, adj p=0.040), but otherwise similar in other patient-reported-outcome-metrics (adj p>0.05 for all). 2Y complications were similar between groups, including for reoperations and major and minor complications (adj p>0.05 for all).

CONCLUSIONS: In Qui type A patients undergoing cMIS with LLIF for ASD, 27.9% develop coronal malalignment, which was associated with worse SF-36 PCS and SRS-22r function/activity. Despite radiographic malalignment, malalignment was not associated with higher 2-year complication rates including reoperations.

Key Points:

- In Qui type A patients undergoing cMIS with LLIF for ASD, approximately 27.9% develop coronal malalignment.
- Development of coronal malalignment was associated with modestly worse SF-36 PCS and SRS-22r function/activity, but similar ODI, pain scores, EQ-5D, EQ-5D VAS, SF-36 MCS, and SRS-22r total score.
- Despite radiographic malalignment, malalignment was not associated with higher 2-year complication rates including reoperations.

INTRODUCTION

Circumferential minimally invasive surgery (cMIS) is an increasingly employed technique used in adult spinal deformity (ASD) to treat scoliosis and correct malalignment.[1,2] Compared to traditional open correction of ASD, cMIS allows for less soft tissue disruption, decreased blood loss, lower surgical infection rates, and fewer major complications.[2] As a result, some surgeons choose to use cMIS to treat ASD over open approaches when feasible.[2,3] cMIS techniques primarily rely on multilevel interbody graft placement, achieved via minimally invasive transforaminal lumbar interbody fusion (TLIF), an anterior lumbar interbody fusion (ALIF), and/or a lateral lumbar interbody fusion (LLIF). Each approach holds its own advantages and disadvantages.[4]

In an LLIF, a retroperitoneal trans- or pre-psoas approach is used to restore the height of intervertebral discs and achieve indirect decompression.[5] This approach serves the advantage of maintaining the anterior (when desired) and posterior longitudinal ligaments allowing for segmental stability and for the placement of wide interbody cages.[4,6] Disadvantages of LLIF include risks to the lumbar plexus, vasculature, and abdominal viscera. In addition, without resection of the anterior longitudinal ligament during an anterior column resection/re-alignment, there is limited single-level lordosis attainable.[1,4,6]

Another potential concern following any cMIS, including an LLIF, is the development of coronal malalignment for patients who were coronally aligned preoperatively, for which there is a dearth of literature. For instance, if a patient was preoperatively balanced with a rigid fractional curve, and the major lumbar curve is straightened with a multilevel LLIF, the patient is at risk of malalignment(**Figure 1**). Coronal alignment is defined by Bao et al. as a coronal vertical axis (CVA) less than 30 mm and is classified as Qiu type A **(Figure 2).**[7] Coronal malalignment is a frequently reported issue after both open and minimally invasive ASD correction and can be associated with worse clinical outcomes.[7-14] This paper aims to investigate the 2-year prevalence of coronal malalignment following LLIF for patients with Qiu type A coronal alignment and to assess if malalignment is associated with worse clinical outcomes.

METHODS

A prospective, multicenter, minimally invasive database for ASD was retrospectively reviewed for this study. The inclusion criteria for the entire dataset include those patients receiving cMIS (i.e., MIS interbody placement along with percutaneous pedicle screw placement) for ASD, who had an age > 18 years, and had a minimum two-year follow-up. ASD was defined as: a minimum coronal Cobb angle (CC) ≥ 20°, sagittal vertical axis (SVA) > 5 cm, pelvic incidence–lumbar lordosis mismatch (PI-LL) ≥ 10°, or pelvic tilt (PT) > 20°. For this study, further inclusion criteria were employed and included patients (1) receiving cMIS with an LLIF and (2) with preoperative CVA < 30 mm. Patients' operations ranged from 1 to 5 level interbody fusions and could also include anterior and posterior approaches.

Two-year clinical outcomes and radiographic parameters were compared for patients categorized as malaligned (MAL) with CVA ≥ 30 mm and aligned (ALIGN) with CVA < 30 mm (**Figure 3**) and were adjusted for factors reaching $p < 0.05$ on univariate comparisons including age, BMI, and ODI. Two-year patient-reported outcome metrics compared included: Oswestry Disability Index (ODI), Numeric Rating Scale (NRS) Back Pain, NRS Leg Pain, EuroQol-5D (EQ-5D), EQ-5D Visual Analogue Scale (EQ-5D VAS), SF-36 Physical Component Summary (PCS), SF-36 Mental Component Summary (MCS), SRS-22r total score and SRS-22r domains for function/activity, pain, self-image, mental health, and satisfaction. Two-year radiographic parameters compared included: CVA, maximum CC, fractional curve Cobb angle (FC), thoracic Cobb angle, SVA, PI-LL, and PT. The complication occurrence: overall, major, minor, and reoperations were also compared. While the ISSG-AO spine complication classification system was used to categorize all complications encountered, for the purposes of this study major and minor complications were defined using the system of classifying complications as published by Glassman et al.[15-17] In addition, 2 reviewers qualitatively evaluated the reason for coronal imbalance in all MAL patients documenting each patient's general demographics, whether they became coronally malaligned 6 weeks following surgery, and the lowest level of instrumentation. In addition, to further help understand the results a novel classification of concave versus convex bias, was documented for all MAL patients. We defined convex or concave bias as follows: Patients with preoperative CVA <= 1.0 cm were classified as having no bias. Patients with CVA > 1.0 cm but <= 3.0 cm along with a C7 plumb line falling on the side of the scoliotic concavity and convexity were considered concave and convex biased, respectively.

RESULTS

Out of the 85 patients who underwent cMIS for ASD and reached two-year follow-up, 43 patients met inclusion criteria and were included in this study. While all included patients received an LLIF, 21 patients (66.6% in the MAL group, and 38.7% in ALIGN group) also received additional ALIF or TLIF. ALIF was performed in 19 patients (66.6% in MAL and 35.5% in ALIGN). TLIF was performed in 3 patients (8.3% in MAL, 6.4% in ALIGN). Of the 43 patients, 72.1% remained coronally aligned (ALIGN) postoperatively whereas 27.9% developed coronal malalignment (MAL). At baseline, MAL were older (73.0 vs. 69.0, p=0.045), had lower BMI (26.09 vs. 29.45, p=0.045), and were less disabled (ODI 42.83 vs. 51.69, p=0.02) as can be seen in Table 1. Otherwise, the groups were well matched statistically for baseline characteristics, including SVA, CVA, and surgical characteristics as shown in Table 1-2. At two-year follow-up, MAL had a statistically greater mean CVA (mean 43.17 vs. 11.48 mm, p<0.001) and a worsened CVA (ΔCVA +26.08 vs. -1.00 mm, p<0.001) compared to ALIGN. Additionally, at two-year follow-up, MAL had a statistically greater SVA (mean 54.08 vs 19.00 mm, p=0.01) driven by a large improvement in the SVA from 48.35 ± 45.85 at baseline to 29.32 ± 40.25 mm at 2Y in the ALIGN group (Table 4). Clinically, MAL was associated with inferior 2Y SF-36 PCS (34.78 vs. 37.42, adjusted p=0.04) and 2Y SRS-22r function activity domain (3.03 vs. 3.36, adjusted p=0.04) as shown in Table 3. Otherwise, both groups had similar ODI, NRS Back Pain, NRS Leg Pain, EQ-5D, EQ-5D VAS, SF-36 MCS, and SRS-22r total score at follow-up (adjusted p>0.05 for all). The most reported complications were radiographic imbalance, implant failure, and musculoskeletal complications (e.g., back pain, neck pain, hip pain, malleolus fracture from a fall). However, two-year complications were similar between MAL and ALIGN, including reoperation rates and major and minor complications (adjusted p>0.05 for all). There was a statistically significant difference between MAL and ALIGN patients in terms of mean operative time; otherwise, both groups had similar operative parameters. Furthermore, we found that 6 of the 12 MAL patients had developed coronal malalignment greater than 30 mm within six weeks of surgery. Qualitatively analyzing these patients, one common reason for early malalignment was insufficient correction of the major and minor curve using a minimally invasive approach. A full qualitative description of each MAL patient can be found in Table 5.

DISCUSSION

The decision to use cMIS compared to open procedures is often debated when strategizing the best approach for achieving optimal outcomes for a particular patient.[18] cMIS was initially developed to decrease morbidity, blood loss, perioperative opioid use, and hospital length of stay.[19] While contemporary studies generally show comparable clinical outcomes postoperatively between open and minimally invasive methods[2], the development of postoperative coronal malalignment following cMIS with LLIF has not been well documented. In this study—the largest prospective ASD cohort study of patients with Qiu Type A alignment undergoing cMIS correction with LLIF—we found that 27.9% of patients developed coronal malalignment. The patients who developed malalignment were older, had a lower baseline ODI, and lower baseline BMI. In terms of outcome implications, we found significantly inferior 2Y SF-36 PCS and 2Y SRS activity scores for MAL compared to those who remained aligned. Interestingly, there were no significant differences in the other quality of life outcome metrics measured.

Regarding surgical technique, there was a statistically significant difference in operative time between the groups, but all other surgical characteristics were similar. There was no statistically significant difference in the approach to L5-S1, whether by LLIF, ALIF, or TLIFX^2 (2, $N = 22$) = 0.241, $p = 0.89$. Notably, there was a statistically significant difference in the 2Y SVA between the MAL and ALIGN groups, driven by a large correction in SVA in the ALIGN group with essentially no change in SVA in the MAL group. There was no significant change in 2Y PI-LL, PT, and other radiographic outcomes.

The difference in SVA between groups may suggest that suboptimal surgical planning and/or level selection may have resulted in the malalignment seen in both the sagittal and coronal planes. This difference in SVA could also explain the worse SF-36 PCS and SRS activity in the MAL group. However, it is important to note, that although the 2Y SVA is higher in the MAL group, the SVA remains within an expected range, especially when considering age-matched SVA.[20,21]

Our 27.9% rate of coronal malalignment suggests that the use of cMIS LLIF, with and without other cMIS techniques, results in similar rates of coronal malalignment compared to open techniques. This finding is significant given the perception that cMIS may contribute to less precise outcomes. Literature on coronal malalignment following open ASD surgery for

previously aligned patients reports rates ranging from approximately 15 to 30 percent.[7,8,22-24] Ploumis et al.[8] showed that 9 out 54 (17%) patients developed coronal malalignment with open techniques 2-5 years postoperatively, defining coronal malalignment as greater than 4 cm. Zhang et al.[22] showed that 16 out of 51 (31%) patients who underwent open ASD surgery developed coronal malalignment on 1-week postoperative radiographic images using Qiu et al. criteria. Makhni et al.[23] investigated a novel kickstand rod open approach for patients with coronal imbalance and found that 1 out of 7 (14%) of patients who were aligned at baseline developed coronal malalignment. This study also had very few patients who met the criteria matching our study. Despite methodological differences, these studies provide an approximate range for the rate of coronal malalignment development after open ASD surgery that is comparable to the rate we found following cMIS.

Notably, a single-center retrospective study by Walker et al.[25] investigated coronal malalignment following cMIS surgery and found 0 out of 26 (0%) patients who were previously aligned at baseline developed coronal malalignment. There are several notable differences between this study and ours. Our study has a larger sample size of 43 patients, uses multicenter prospective data, and specifically examines two-year follow-up after LLIF, rather than one-year.

Despite the current inability to conduct posterior column osteotomies[26] and a limited ability to perform rod compression/distraction/coronal bending techniques with cMIS, we identified similar rates of coronal malalignment following cMIS surgery compared to open surgery for ASD. Our findings may be explained by the fact that the surgical group in this study consists of high volume cMIS deformity surgeons. The experience employed for patient selection and surgical execution—paying particularly close attention to vertebral (e.g., L4 or L5) obliquity and/or pelvic obliquity—may result in a lower rate of coronal malalignment. Leveling the L4 and L5 vertebrae and treating the fractional curve have been shown to be pivotal in avoiding coronal malalignment and achieving better outcomes.[24,27-29] To achieve a horizontal L4 vertebrae, wide grafts may be placed within the fractional curve. Alternatively, asymmetries in the vertebral bodies can be dealt with using asymmetric cage placement. If a partial fusion is selected, the impact of the unfused fractional curve on ultimate coronal balance needs to be anticipated.

In this study, we found that the preoperative obliquity and the slope of superior L4 was not statistically significant between MAL and ALIGN groups (P=0.804, P=0.87 for obliquity and

slope respectively). While we see a similar occurrence of coronal malalignment in this study, there are many instances where open procedures are preferred, and hybrid surgery, such as osteotomies after MIS, may be considered for high-risk patients.[30]

Similar to the Qiu classification, the preoperative Obeid classification is helpful in determining the optimal operative strategy to mitigate postoperative coronal malalignment. Obeid classifies coronal imbalance as either concave coronal malalignment (type 1, C7 plumb line > 2 cm, analogous to Qiu type B) or convex coronal malalignment (type 2, C7 plumb line > 2 cm, analogous to Qiu Type C) with additional modifiers for stiffness of the main coronal curve, the mobility of the lumbosacral junction, and the degeneration of the lumbosacral junction.[31] Although the patients in this study were all coronally balanced preoperatively, the principle of assessing the sidedness of the C7 plumb line relative to the main curve convexity/concavity remains. For instance, if a patient's C7 plumb line falls on the concave side of the main curve, a limited fusion of the main curve alone may be reasonable. However, if a patient has a C7 plumb line that falls on the convex side of the main curve, a fusion addressing the fractional curve (with or without treatment of the major curve) may be considered. Applying this philosophy to our data, we found no significant relationship between preoperative concave or convex bias and the development of malalignment postoperatively X^2 (1, N = 21) = 0.772, p = 0.38.

Achieving coronal alignment is particularly crucial, as there is well-documented evidence linking patient clinical outcomes and coronal malalignment.[2,7,13,14,32] In our study, we demonstrate a negative relationship between SF-36 PCS and SRS activity and the development of coronal malalignment in patients. In addition, although there was no significant difference in the Δ SF-36 PCS at 2 years (Adjusted p= 0.33), there were more patients who reached MCID (>7.7 change)[33] for ΔSF-36 PCS in ALIGN (52.1%) compared to MAL (37.5%). A study by Plais et al.[14] similarly showed that patients with a CVA over 3 cm had a significantly worse Oswestry Disability Index, SF-36 PCS, and SRS 22. While some debate exists into the relative importance of SVA versus CVA for postoperative outcomes[34], our data adds to the mounting evidence that proper postoperative coronal alignment is still important in many aspects of the patient's post-operative experience.

There are several limitations to note in our study. First, although the data in this study was collected prospectively, the analysis was done retrospectively and holds the associated limitations. It is not possible to retrospectively ascertain the primary goal of surgery, such as

whether surgery was intended to address a patient's spinal deformity. However, we believe this study still addresses our proposed question. In addition, prospective data does have the advantage of eliminating bias in such aspects as the reporting of surgical complications. Second, a difference in postoperative SVA between the MAL and ALIGN group makes it difficult for us to attribute differences in quality-of-life measurements to coronal malignment alone. Additionally, though we observed a significant difference in SF-36 PCS and SRS-22r function/activity between MAL and ALIGN, it is important to state that statistical significance does not necessarily equate to clinical significance. Third, our study analyzes patients who had a surgery which included a component of LLIF. The inclusion of patients who also had other interbody procedures in addition to an LLIF, such as TLIF or ALIF, may influence our findings. Our results should be interpreted in this context. Finally, slight variations in surgical techniques between different surgeons and differing instrumentation and technologies utilized may lead to differing outcomes in some patients. Notwithstanding these weaknesses, this study addresses a hitherto underreported specific outcome measure. Moreover, this study is the largest study of cMIS adult spinal deformity correction and the analysis of post-operative coronal malalignment after LLIF.

CONCLUSION

Our results showed that 27.9% of pre-operatively aligned patients undergoing cMIS surgery with LLIF for ASD developed coronal malalignment and developing malalignment postoperatively was associated with modestly worse SF-36 PCS and SRS-22r function/activity. This association was also mediated by the worse sagittal alignment observed in the coronally malaligned cohort. Paying particularly close attention to the fractional curve, ensuring that L4 and L5 are horizontal, and identifying the pre-operative Qiu type may lead to avoiding postoperative coronal malalignment. Our results indicate that cMIS results in comparable rates of coronal alignment compared to open surgeries that have a malalignment rate of approximately 15-30%.

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Figure 1. Postoperative development of coronal malalignment in a patient coronally aligned at baseline.

79-year-old-female who presents with back pain for over 10 years (NRS back 6/10) along with leg weakness and gait imbalance . (A) AP and (B) lateral preoperative 36-inch plain radiographs demonstrate SVA 13.7 cm, PI-LL mismatch 27.3 degrees, PT: 29.4 degrees, CVA 0.2 cm, and maximum coronal cobb 58.4 degrees. She underwent a staged L2-5 LLIF, L5-S1 ALIF and T11-pelvis PSF. (C) AP and (D) lateral postoperative 36-inch plain radiographs demonstrate the development of coronal imbalance, with CVA 7.5 cm, along with SVA 3.7 cm, PI-LL mismatch 15.1 degrees, PT: 19.5 degrees, and maximum coronal cobb 6.5 degrees.

Figure 2. Qiu Classification for coronal malalignment.

Bao et al.[1] define coronal alignment by determining the relationship between the C7-plumb line (C7PL) and the central sacral vertical line (CSVL). In Qiu Type A, patients are coronally aligned with the C7PL falling within 3cm of the CSVL. Patients who are coronally malaligned may fall into either Qiu Type B or Qiu Type C classification. In Qiu Type B, the C7PL is located more than 3cm from the CSVL, and the C7PL falls on the side of the scoliotic concavity. In Qiu Type C, the C7PL is also located more than 3cm from the CSVL, but the C7PL falls on the side of the scoliotic convexity.

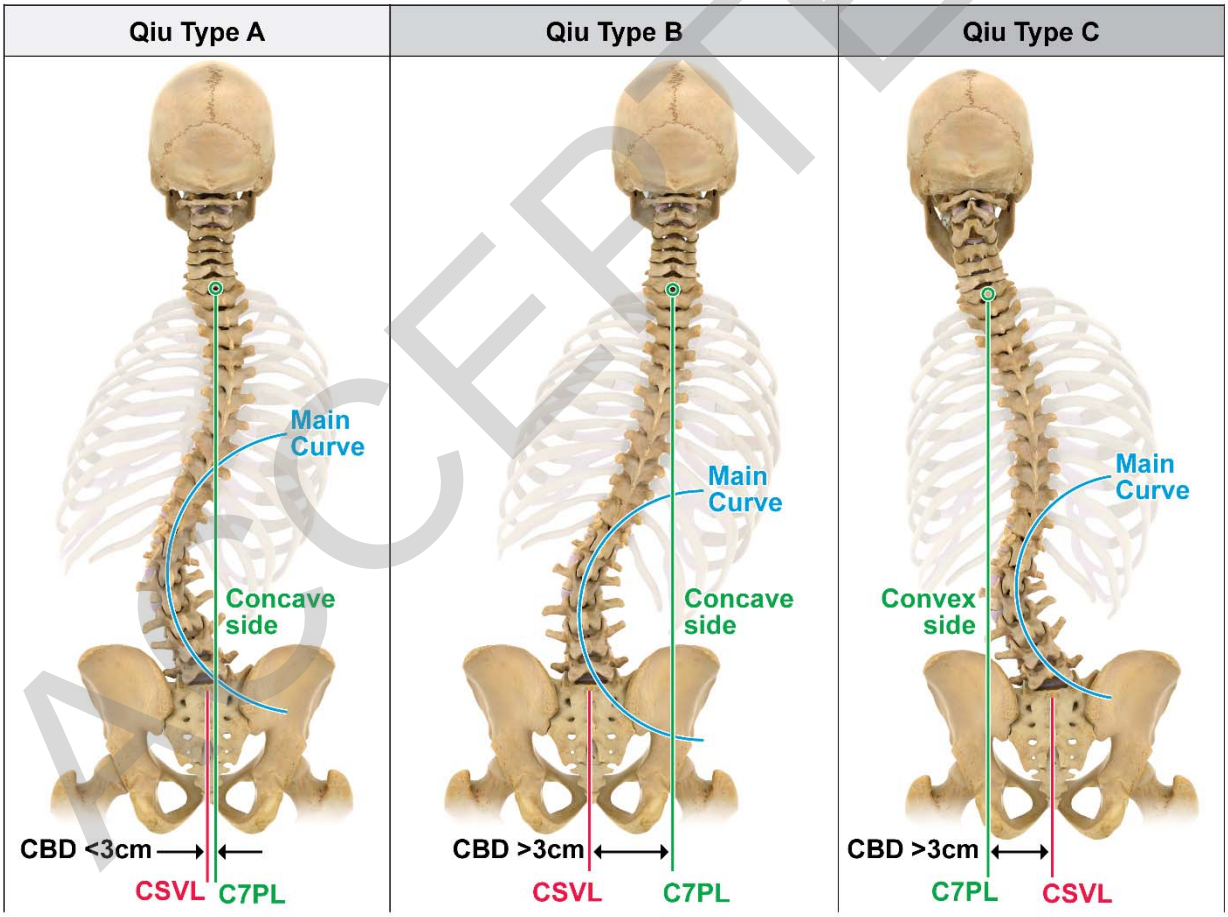

Figure 3. Postoperatively retained coronal alignment in a patient well-aligned at baseline. 74-year-old-female who presents with over 10 years of back pain and leg pain (NRS back 6/10 and NRS leg 6/10). (A) AP and (B) lateral preoperative 36-inch plain radiographs demonstrate SVA: 7.9 cm, PI-LL mismatch 11.1 degrees, PT 20.1 degrees, CVA 0.8 cm, and maximum coronal cobb 29.1 degrees. She underwent an L1-L5 LLIF + L5-S1 ALIF, L1-S1 anterior instrumentation, and L4-S1 posterior instrumentation. (C) AP and (D) lateral postoperative 36-inch plain radiographs demonstrate that the patient had retained coronal alignment, with CVA 1.3 cm, along with SVA 3.0 cm, PI-LL mismatch 0.8 degrees, PT 19.8 degrees, and maximum coronal cobb 11.8 degrees.

TABLE 1

Summary Statistics of Baseline Demographics			
	ALIGN	MAL	p value
Females	24 (77.4)	7 (22.6)	0.19
Age, yrs	69 ± 7.02	73 ± 6.12	0.045*
Body Mass Index	29.45 ± 6.14	26.09 ± 4.54	0.045*
Charlson Comorbidity Index	2.16 ± 1.37	2.42 ± 1.44	0.30
Frailty Index	3.57 ± 1.3	3.64 ± 1.12	0.44

Summary Statistics of Baseline PROM Scores			
	ALIGN	MAL	p value
Oswestry Disability Index	51.69 ± 11.67	42.83 ± 11.71	0.02*
Numerical Rating Scale Back	7.7 ± 2.02	7.17 ± 2.25	0.23
Numerical Rating Scale Leg	5.69 ± 3.62	5.08 ± 3.15	0.31
EQ-5D	0.75 ± 0.05	0.75 ± 0.06	0.38
EQ-5D Visual Analogue Scale	59.46 ± 22.82	64.44 ± 20.22	0.28
SF-36 PCS	27.4 ± 5.01	28.28 ± 5.77	0.32
SF-36 MCS	45.02 ± 12.98	44.05 ± 11.84	0.42
SRS Activity	2.68 ± 0.64	2.8 ± 0.69	0.31
SRS Pain	2.2 ± 0.57	2.35 ± 0.76	0.26
SRS Appearance	2.61 ± 0.75	2.56 ± 0.69	0.43
SRS Mental	3.55 ± 0.77	3.49 ± 0.83	0.41
SRS Satisfaction	3.09 ± 1.04	2.82 ± 0.64	0.22
SRS Total	2.79 ± 0.47	2.8 ± 0.45	0.48

Summary Statistics of Radiographic Baseline			
	ALIGN	MAL	P value
Coronal Vertical Axis	12.61 ± 7.77	17.17 ± 11.12	0.07
Fractional Curve	10.69 ± 6.75	13.29 ± 9.91	0.35
Max Coronal Cobb Angle	26.37 ± 12.21	31.18 ± 16.07	0.16
Pelvic Incidence	51.23 ± 13.82	53.25 ± 10.66	0.33
Pelvic Tilt	22.16 ± 9.49	22.67 ± 7.58	0.44
PI-LL	11.16 ± 16	17.67 ± 11.24	0.10
Sagittal Vertical Axis	48.35 ± 45.85	58.83 ± 44.82	0.25
Baseline Apex †			0.99
T7	1 (3.2)	-	-
T8	1 (3.2)	-	-
T9	1 (3.2)	-	-
T12	2 (6.4)	-	-
L1	4 (12.9)	3 (25.0)	-
L2	12 (38.7)	2 (16.6)	-
L3	9 (29.0)	6 (50.0)	-

Fractional Curve Apex †			0.50
L4	1 (3.2)	-	-
L5	12 (38.7)	7 (58.3)	-
Lumbar Sacral Cobb Angle	11 ± 6.75	13 ± 9.91	0.49

PROM = Patient Reported Outcome Metric.
PCS = Physical Component Summary.
MCS = Mental Component Summary.
SRS = Social Responsiveness Scale.
PI-LL = Pelvic Incidence- Lumbar Lordosis Mismatch.
Values presented in parentheses represent percentages.
Values are shown as mean ± SD.
† Data can not be determined for the baseline of every patient since curve may not be pronounced enough. Percentages are still taken as part of all patients in each outcome group.

TABLE 2

Surgical Characteristics			
	ALIGN	MAL	P value
Staged	9 (29.0)	4 (33.3)	0.53
Mean levels of Interbody Fusion	3.09 ± 1.53	3.75 ± 1.21	0.10
UIV			0.27
UIV T7-T12	10 (32.3)	6 (50.0)	-
UIV L1-L5	21 (67.7)	6 (50.0)	-
LIV			0.07
LIV T11-L5	12 (38.7)	1 (8.3)	-
LIV S1	8 (25.8)	7 (58.3)	-
LIV Ilium	11 (35.5)	4 (33.3)	-
Additional ALIF	11 (35.5)	8 (66.6)	0.80
Additional TLIF	2 (6.4)	1 (8.3)	0.36
Decompression	6 (19.4)	2 (16.7)	0.61
Mean EBL	270.64 ± 235.89	460 ± 615.49	0.07
Mean Operative Time	355.16 ± 182.88	492.75 ± 272.21	0.03*
Complications	21 (67.7)	8 (66.7)	0.20
Major Complications	6 (19.4)	3 (.25)	0.49
Minor Complications	12 (38.7)	5 (41.7)	0.56
Reoperations	10 (32.3)	1 (8.3)	0.11

UIV = Upper Instrumented Vertebrae.
LIV = Lower Instrumented Vertebrae.
EBL = Estimated Blood Loss.
Values presented in parentheses represent percentages.
Values are shown as mean ± SD.

TABLE 3

Summary Statistics 2 yr Postoperative Radiographic Outcomes			
	ALIGN	MAL	p value
Coronal Vertical Axis	11.48 ± 8.5	43.17 ± 11.11	0.00*
Fractional Curve	6.54 ± 6.4	5.86 ± 3.58	0.40
Max Coronal Cobb Angle	16.80 ± 10.05	13.55 ± 9.27	0.18
Pelvic Incidence	51.74 ± 13.96	52.58 ± 11.12	0.43
Pelvic Tilt	19.10 ± 9.59	19.92 ± 7.94	0.40
PI-LL	0.26 ± 13.01	6.08 ± 13.66	0.10
Sagittal Vertical Axis	19.00 ± 38.94	54.08 ± 55.45	0.01*

Change in Statistics 2 yr Postoperative vs Preoperative			
	ALIGN	MAL	p value
Δ Coronal Vertical Axis	-1.00 ± 11.17	26.08 ± 18.52	0.00*
Δ Fractional Curve	-3.85 ± 7.32	-7.34 ± 10.33	0.19
Δ Max Coronal Cobb Angle	-9.77 ± 9	-17.73 ± 17.3	0.09
Δ Pelvic Incidence	0.39 ± 1.86	-0.50 ± 1.57	0.08
Δ Pelvic Tilt	-3.03 ± 7.53	-2.75 ± 5.79	0.45
Δ PI-LL	-10.94 ± 12.29	-11.67 ± 16.18	0.44
Δ Sagittal Vertical Axis	-29.32 ± 40.25	-4.67 ± 62.21	0.07

PI-LL = Pelvic Incidence- Lumbar Lordosis Mismatch.
Values are shown as mean ± SD.

TABLE 4

Summary Statistics of 2 yr Postoperative PROM Scores				
	ALIGN	MAL	p value	Adjusted p value
Oswestry Disability Index	28.71 ± 19.88	28.60 ± 16.63	0.49	0.30
Numerical Rating Scale Back	3.88 ± 3.06	4.30 ± 2.63	0.35	0.06
Numerical Rating Scale Leg	3.19 ± 3.09	3.00 ± 2.16	0.43	0.93
EQ-5D	0.81 ± 0.09	0.78 ± 0.04	0.11	0.30
EQ-5D Visual Analogue Scale	72.72 ± 18.35	69.58 ± 18.15	0.31	0.45
SF-36 PCS	37.42 ± 9.12	34.78 ± 9.69	0.23	0.04*
SF-36 MCS	53.35 ± 11.38	49.76 ± 9.37	0.20	0.86
SRS Activity	3.36 ± 0.74	3.03 ± 0.81	0.23	0.04*
SRS Pain	3.38 ± 0.81	3.16 ± 0.73	0.45	0.12
SRS Appearance	3.02 ± 1.01	3.25 ± 0.78	0.52	0.96
SRS Mental	3.45 ± 0.91	3.55 ± 0.72	0.75	1.00
SRS Satisfaction	4.15 ± 0.83	4.14 ± 0.95	0.96	0.86
SRS Total	3.38 ± 0.71	3.34 ± 0.57	0.44	0.20
Change in Statistics 2 Yr Postoperative vs Preoperative PROM Scores				
	ALIGN	MAL	p value	Adjusted p value
Δ Oswestry Disability Index	-23.80 ± 22.28	-13.20 ± 10.84	0.03	0.35
Δ Numerical Rating Scale Back	-4.04 ± 3.61	-3.30 ± 2.67	0.28	0.99
Δ Numerical Rating Scale Leg	-2.16 ± 4.93	-3.10 ± 2.81	0.24	0.80
Δ EQ-5D	0.06 ± 0.09	0.04 ± 0.08	0.25	0.99
Δ EQ-5D Visual Analogue Scale	10.05 ± 25.45	3.33 ± 28.39	0.27	0.25
Δ SF-36 PCS	10.02 ± 10.49	7.14 ± 6.26	0.24	0.33
Δ SF-36 MCS	5.75 ± 12.35	6.16 ± 10.52	0.47	0.58
Δ SRS Activity	0.76 ± 0.85	0.26 ± 0.95	0.07	0.19
Δ SRS Pain	1.17 ± 0.81	1.05 ± 0.78	0.34	0.83
Δ SRS Appearance	0.41 ± 1.21	0.71 ± 0.69	0.23	0.33
Δ SRS Mental	-0.12 ± 1.11	0.02 ± 0.6	0.36	0.90
Δ SRS Satisfaction	1.04 ± 1.36	1.30 ± 1.14	0.30	0.64
Δ SRS Total	0.60 ± 0.77	0.59 ± 0.54	0.49	0.76

PROM = Patient Reported Outcome Metric.
PCS = Physical Component Summary.
MCS = Mental Component Summary.
SRS = Social Responsiveness Scale.
Values presented in parentheses represent percentages.
Values are shown as mean ± SD.

TABLE 5

Patient	Age	Gender	Prior Spine Surgery	Preoperative Coronal Vertical Axis (mm)	Bias at Baseline*	Surgical Approach	Surgical Characteristics		Malaligned at 6 week post operative follow up (6 week Coronal Vertical Axis in mm)	2 yr Coronal Vertical Axis (mm)	Qualitative Reasoning for Coronal Malalignment
							ALIF	Lowest Instrumented Vertebra			
1	81	M	L4-S1 fusion in place	27	Concave	T12-L4 fusion, T12-L4 LLIF	No	L4	Y (37)	46	Surgical correction of the major curve coronally malaligned the patient. Patient may have benefited from less correction of the lumbar curve, taking into account the fused fractional curve, and an open posterior technique.
2	79	M	N/A	10	None	L3-S1 fusion, L3-S1 LLIF	No	S1	N (17)	37	Patient was fused with L4 not horizontalized resulting in eventual coronal decompensation. Patient may have benefited from a hybrid approach or asymmetric cage to horizontalize L4.
3	72	F	L1-S1 fusion in place with L1-L2 and L2-L3 standalone LLIF	18	Convex	L3 PSO with L1-L2 fusion	No	S1	Y (37)	31	Patient was fused with L4 not horizontalized. With the PSO and extension of the rod portion of the construct, the corrected L1-L3 segments relative to L4 resulted in coronal malalignt. Patient may have benefited from a slight asymmetry in the PSO.
4	70	F	N/A	27	Concave	L2-L4 fusion, L2-L4 LLIF	No	L4	Y (38)	45	Surgical correction of the lumbar curve (apex L3-L4) coronally malaligned the patient. Patient may have benefited from fusing two superior levels.
5	66	M	L2-L5 fusion in place with a large residual curve	2	None	T12-S1 fusion, L1-L2 and L3-L4 LLIF, L5-S1 ALIF	Yes	S1	N (6)	46	LLIF at L3-L4 and L1-L2 resulted in rightward coronal malalignment. Patient may have benefited from an open procedure with type 2 osteotomies that are beyond corrective capabilities of lateral cages.
6	75	M	N/A	28	Convex	L1-S1 fusion, L2-L4 LLIF, L4-S1 ALIF, L1-S1 PLIF	Yes	S1	N (18)	44	Coronal decompensation over time. Patient may have benefited from open procedure that extended into thoracic region and a thoracolumbar fusion.
7	66	F	L3-5 Dynamic Stabilization System (Dynesys) in place	18	Convex	L2-L1 fusion, L2-L3 LLIF, L5-S1 ALIF	Yes	S1	N (18)	41	Patient was fused with L4 not horizontalized but was initially able to compensate with the cephalad unfused segments. She coronally decompensated over time. Patient may have benefited from horizontalizing L4 by an LLIF at L4-L5.
8	80	F	N/A	24	Convex	L1-ilium fusion, with L1-5 LLIF, L5-S1 ALIF, L1-ilium PLIF	Yes	Ilium	N (19)	34	Patient was fused with L4 not horizontalized but was initially able to compensate with the cephalad unfused segments. She coronally decompensated over time. Patient may have benefited from a horizontalizing L4 with an asymmetrically placed L4-L5 ALIF or use of an open technique with an asymmetric cage.
9	80	F	N/A	0	None	T11-ilium fusion, L2-L5 LLIF, L5-S1 ALIF	Yes	Ilium	Y (104)	75	Appropriate correction of the large major thoracolumbar curve resulted in leftward coronal malalignment. Patient may have benefited from an open approach with multilevel osteotomy.
10	66	F	N/A	22	Concave	T10-ilium fusion, with L1-L5 LLIF, L5-S1 ALIF	Yes	Ilium	Y (41)	42	Patient was fused with L4 not horizontalized resulting in eventual coronal decompensated. Patient may have benefited from horizontalization of L4 with L4-L5 ALIF placed asymmetrically, an asymmetric cage, and a hybrid approach (open posterior technique) with osteotomies.
11	66	M	N/A	29	Concave	T11-S1 fusion, L2-L5 LLIF, L5-S1 ALIF	Yes	S1	Y (36)	40	Insufficient correction of the major curve resulted in coronal malalignment. Patient may have benefited from more cephalad level of lateral cages or open deformity surgery with osteotomies.
12	75	F	N/A	1	None	T10-ilium fusion, L2-L5 LLIF, L5-S1 ALIF	Yes	Ilium	Y (35)	37	Patient was fused with L4 not horizontalized resulting in eventual coronal decompensation. Patient may have benefited from horizontalization of L4 with L4-L5 ALIF placed asymmetrically, an asymmetric cage, and a hybrid approach (open posterior technique) with osteotomies

*All patients in this cohort were coronally aligned at baseline (i.e., CVA <= 3.0 cm). However, we establish a novel classification determining whether the C7 plumb line falls on the side of the scoliotic concavity or convexity in this coronally aligned cohort preoperatively. Patients with preoperative CVA <= 1.0 cm were classified as having no bias. Patients with CVA > 1.0 cm but <= 3.0 cm along with a C7 plumb line falling on the side of the scoliotic concavity and convexity were considered concave and convex biased, respectively.