Original Article

Pre-contoured patient-specific rods result in superior immediate sagittal plane alignment than surgeon contoured rods in adolescent idiopathic scoliosis

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Background: Adolescent idiopathic scoliosis (AIS) surgery typically involves posterior spinal fusion (PSF) using rods contoured by the surgeon, which may be time-consuming and may not reliably restore optimal sagittal alignment. However, pre-contoured patient-specific rods may more optimally restore sagittal spinal alignment. This study evaluates the radiographic outcomes of AIS patients who underwent PSF utilizing surgeon contoured *vs.* pre-contoured rods.

Methods: This is a retrospective cohort study of AIS patients who underwent PSF with either surgeon contoured or pre-contoured rods. Demographics, Lenke classification, fused levels, osteotomies, estimated blood loss (EBL), and surgical time were also obtained via chart review. Coronal curve magnitude, T5–T12 thoracic kyphosis (TK), lumbar lordosis (LL), pelvic incidence (PI), PI-LL mismatch, and T1 pelvic angle (TPA) were obtained pre-operatively, postoperatively and at last follow up. Outcome measures included rate of achievement of postoperative radiographic alignment goals (TK between 20 and 40 degrees, PI-LL mismatch within 10 degrees, and TPA <14 degrees). Predicted post-operative sagittal alignment was also compared with observed measurements. Student's and paired *t*-tests were performed to determine significant mean differences for continuous variables, and chi-square for categorical variables.

Results: No differences were found in demographics, Lenke classification, preop radiographic measurements, fused levels, osteotomies, EBL, and surgical time in the surgeon contoured cohort (n=36; average follow up 11.3 months) and pre-contoured cohort (n=22; average follow up 9.7 months). At last follow up, 95.5% of patients with pre-contoured rods *vs.* 61.1% of patients with surgeon contoured rods (P=0.004) met TK goal. During assessment of first standing postoperative X-ray, 72.7% of patients with pre-contoured rods *vs.* 33.3% of patients with surgeon contoured rods met PI-LL mismatch goal (P=0.004). Other radiographic measurements were similar. Artificial intelligence (AI) predicted and observed differences for the pre-contoured group were 3.7 for TK (P=0.005), −7.6 for PI-LL mismatch (P=0.002), and −2.6 for TPA (P=0.11).

Conclusions: AI and pre-contoured rods help achieve global sagittal balance with high accuracy and improved kyphosis restoration and PI-LL mismatch than surgeon contoured rods in AIS patients.

Keywords: Adolescent idiopathic scoliosis (AIS); pre-contoured rods; patient-specific rods; surgeon contoured rods; radiographic outcomes

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Submitted Jan 06, 2024. Accepted for publication Mar 28, 2024. Published online May 29, 2024.
doi: 10.21037/jss-24-1
View this article at: https://dx.doi.org/10.21037/jss-24-1

Introduction

Adolescent idiopathic scoliosis (AIS) involves coronal, sagittal, and axial plane spinal deformity in patients 10–18 years of age and has an annual prevalence as high as 5% (1-3). Bracing may be utilized for minor deformity, but more significant curves (cobb angle >45 degrees) or rapidly progressing curves benefit from surgical management to prevent curve progression and cardiopulmonary dysfunction (2,4-6). Surgical deformity correction can also help restore a well-balanced posture and may minimize disability and back pain (6). However, despite the benefits of posterior spinal fusion (PSF), the most common surgical procedure for AIS, it can be relatively morbid and associated with neurologic damage, high rates of blood loss, extended hospital stays, pseudoarthrosis, decompensation with increased sagittal deformity, and potentially irreversible long-term complications including degenerative disc disease (6-10). Thus, great efforts and advancements have been made in AIS surgery to improve surgical and clinical outcomes.

However, despite preoperative planning, achieving optimal postoperative spinal alignment in all planes is not always accomplished (11). Traditionally, spinal rods have been contoured intraoperatively based off surgeon experience which may not achieve the most optimal sagittal alignment (11,12). Use of machine learning and artificial intelligence (AI) software to evaluate preoperative images and provide optimal surgical plans, including instrumentation parameters and rod configurations, has been instrumental for preoperative planning and achieving improved postoperative spinal alignment in AIS cases (13). In addition, patient-specific rods have been developed to further improve not only postoperative alignment but also intraoperative efficiency as rods contoured by the surgeon can be error prone and prolong operative time (14). Sardi *et al.* demonstrated that even experienced spine surgeons tend to overbend rods compared to the desired angle which could impact patient outcomes and risk proximal junctional failure (12).

There remains a paucity of literature, with inclusion of a comparison group, that investigate outcomes of rod contouring modality in AIS patients. Thus, the aim of this study was to compare the radiographic and surgical outcomes for adolescent patients undergoing PSF for AIS with either surgeon contoured or pre-contoured patient-specific rods. We hypothesized that AIS patients with pre-contoured rods will have improved radiographic and surgical outcomes compared to patients with surgeon contoured rods. We present this article in accordance with the STROBE reporting checklist (available at https://jss.amegroups.com/article/view/10.21037/jss-24-1/rc).

Highlight box

Key findings
- Adolescent idiopathic scoliosis (AIS) patients with pre-contoured rods had improved sagittal alignment relative to those with surgeon contoured rods.
- Thoracic kyphosis (TK) was between 20 and 40 degrees in 95.5% of patients with pre-contoured rods *vs.* 61.1% of patients with surgeon contoured rods at last follow up.
- Pelvic incidence-lumbar lordosis (PI-LL) mismatch was within 10 degrees at initial postoperative visit in 72.7% of patients in the pre-contoured cohort *vs.* 33.3% of patients in the surgeon contoured cohort.
- Mean differences between artificial intelligence predicted and observed values for the pre-contoured group were close to target value.

What is known and what is new?
- Surgeon contouring of rods for AIS patients may be time-consuming and may not reliably restore optimal sagittal alignment.
- Use of patient-specific pre-contoured rods is growing in popularity but there remains a paucity of literature, with inclusion of a comparison group, that investigate outcomes of rod contouring modality in AIS patients.
- This study demonstrates improved sagittal alignment (TK and PI-LL mismatch) in the pre-contoured rods cohort with high preoperative planning accuracy.

What is the implication, and what should change now?
- Pre-contoured rods may help predict global sagittal balance and achieve more optimal kyphosis restoration and PI-LL mismatch than surgeon contoured rods in AIS patients.
- Further prospective studies with larger sample sizes, long-term follow up and additional investigation of rod material impacts are needed to corroborate these findings and follow the relationship of these sagittal parameters to patient reported outcomes.

Methods

Our study protocol was reviewed by the Institutional

Review Board of Yale University (IRB Protocol ID: 2000033586). The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). Individual consent for this retrospective analysis was waived. A retrospective cohort study of prospectively collected data of two groups of AIS patients who underwent PSF with surgeon contoured rods (December 2019–February 2023) or patient-specific rods (September 2021–October 2022) was performed. Patients were not randomized and underwent surgery by a single orthopedic spine surgeon at an academic institute who was transitioning from surgeon contoured to the use of patient-specific rods for AIS patients. Exclusion criteria included <6 months of postoperative follow up and lack of full spine standing anteroposterior and lateral radiographs preoperatively and postoperatively.

Patient demographics, Lenke classification, number of fused levels and osteotomies, estimated blood loss (EBL), and surgical time were obtained via chart review.

Radiographic measurements including coronal curve magnitude, T5–T12 thoracic kyphosis (TK), lumbar lordosis (LL), pelvic incidence (PI), PI-LL mismatch, and T1 pelvic angle (TPA) were obtained by an orthopedic surgeon pre-operatively, postoperatively and at last follow up utilizing Medicrea software for pre-contoured cohort and Orthoview software for surgeon contoured cohort. Adaptive spine intelligence software was utilized to predict post-operative sagittal alignment which was compared with observed measurements. The primary outcome measure was rate of achievement of postoperative radiographic alignment goals (TK between 20 and 40 degrees, PI-LL mismatch within 10 degrees, and TPA <14 degrees) (15-19). Number of patients with thoracic hypokyphosis (TK <10 degrees) and thoracic hyperkyphosis (TK >40 degrees) was also noted. Secondary outcome measures included number of osteotomies, surgical time, and EBL in both cohorts as well as accuracy of preoperative plans in the pre-contoured cohort.

Surgeon contoured rod cohort surgical technique

Posterior dissection and exposure of appropriate levels was carried out and confirmed on fluoroscopy. Posterior column osteotomies (PCOs) were performed if needed. Freehand technique or three-dimensional (3D) printed mechanical guides were utilized for pedicle screw placement with fluoroscopy and appropriate placement was confirmed with triggered electromyography (EMG) and/or intraoperative 3D imaging following screw placement. The spine was then decorticated utilizing a high-speed burr. 5.5 or 6.0 mm titanium (n=30) or cobalt chromium (n=6) rods were utilized, and differential contouring with a French bender (typically left rod with over kyphosis and right rod with under kyphosis) was performed intraoperatively by the surgeon for spinal derotation. Placement of left rod was typically performed first, and a rod roll or rod rotation maneuver was utilized to convert the scoliosis into TK. Set screws were placed and provisionally tightened. The right sided rod was then typically placed in cantilever fashion to “push down” on the right rib hump. Set screws were then provisionally tightened on the right. Subsequently, segmental direct vertebral rotation was performed at all levels. Distraction was then typically performed at the top of the left rod to level the shoulders if needed. Appropriate derotation and TK restoration was confirmed on fluoroscopy.

Patient-specific pre-contoured rod cohort surgical technique

Medicrea’s UNiD Adaptive Spine Intelligence software was utilized for preoperative planning and to develop patient-specific pre-contoured rods prior to surgery. Surgical technique was similar to the surgeon contoured technique except that pre-contoured, either 5.5 or 6.0 mm titanium (n=1) or cobalt chromium (n=20) were utilized and did not require contouring intraoperatively. One patient had a combination of cobalt chromium (left) and titanium (right) rods that were used. The rods were not differentially contoured in all patients in the pre-contoured cohort.

Subgroup analysis

A subgroup analysis was carried out to evaluate for radiographic differences based on rod material. Radiographic measurements of the six patients in the surgeon contoured cohort and 20 patients in the pre-contoured cohort who had cobalt chromium rods were compared. Note one patient in the pre-contoured cohort who had a cobalt chromium rod (left) and titanium rod (right) was excluded from this particular analysis.

Statistical analysis

Various patient characteristics, radiographic measurements, and patient-reported outcomes were compared between the patients that underwent fusion with the surgeon contoured rods and the pre-contoured rods. Statistical analysis was

Table 1 Surgeon contoured *vs.* pre-contoured cohort: demographics, baseline characteristics, follow up and surgical outcomes

Parameters	Surgeon contoured (n=36)	Pre-contoured (n=22)	P value
Age (years)	14 (1.0)	14 (2.0)	0.14
Sex			0.45
Female	21 (58.3)	15 (68.2)	
Male	15 (41.7)	7 (31.8)	
Lenke			0.28
1	15 (41.7)	14 (63.6)	
2	6 (16.7)	1 (4.5)	
3	3 (8.3)	2 (9.1)	
4	1 (2.8)	0 (0.0)	
5	4 (11.1)	4 (18.2)	
6	7 (19.4)	1 (4.5)	
Risser			0.39
0	4 (11.1)	0 (0.0)	
1	3 (8.3)	3 (13.6)	
2	2 (5.6)	0 (0.0)	
3	6 (16.7)	3 (13.6)	
4	18 (50.0)	15 (68.2)	
5	3 (8.3)	1 (4.5)	
Follow up (months)	11.3 (3.3)	9.7 (2.7)	0.059
Levels fused	9.9 (2.5)	10 (2.7)	0.92
Surgical time (hours)	4 (2.3)	4.6 (0.9)	0.20
Navigated	24 (66.7)	11 (50.0)	0.21
EBL (mL)	438 (190.0)	383 (183.0)	0.28
Transfused	24 (66.7)	19 (86.4)	0.10
Osteotomy	2 (5.6)	3 (13.6)	0.29

Data are presented as mean (SD) or n (%). EBL, estimated blood loss; SD, standard deviation.

performed using Student's and paired *t*-tests to determine significant mean differences for continuous variables. Chi-squared analysis was performed for categorical variables. All statistical analysis was performed using SPSS (IBM SPSS Statistics, Version 28.0. Armonk, NY, USA). An alpha of 0.05 and beta of 0.20 was set for analyses.

Results

Forty-nine patients were initially identified in the surgeon countered cohort and 35 in the pre-contoured cohort. Thirty-six patients in the surgeon contoured cohort (average last follow up =11.3 months) and 22 in the pre-contoured cohort (average last follow up =9.7 months) met the inclusion criteria. Exclusion of patients was due to insufficient follow up (<6 months). No statistically significant differences were noted with regards to demographics, Lenke classification, preoperative radiographic measurements, number of fused levels and osteotomies, EBL, and surgical time (*Table 1*).

TK was between 20 and 40 degrees in 95.5% of patients with pre-contoured rods *vs.* 61.1% of patients with

Table 2 Preoperative, postoperative and final follow up radiographic measurements

Parameters	Surgeon contoured (n=36)	Pre-contoured (n=22)	P value
Preoperative			
Cobb angle (degrees)	58.1 (9.6)	60.1 (12.5)	0.48
TK (degrees)	22 (13.5)	24.5 (14.6)	0.51
LL (degrees)	58.8 (12.8)	52.9 (12.5)	0.09
PI (degrees)	48.5 (12.5)	46 (10.4)	0.43
PI-LL mismatch (degrees)	−10.3 (13.9)	−6.9 (13.2)	0.37
TPA (degrees)	4.6 (9.3)	3.4 (8.0)	0.62
TK within 20–40 degrees	15 (41.7)	10 (45.5)	0.78
PI-LL within 10 degrees	16 (44.4)	11 (50.0)	0.68
TPA <14 degrees	33 (91.7)	20 (90.9)	0.92
Postoperative			
Cobb angle (degrees)	12.5 (4.9)	14.9 (6.2)	0.11
TK (degrees)	25.9 (11.7)	27.7 (6.2)	0.51
LL (degrees)	60.8 (10.8)	47 (10.6)	<0.001*
PI-LL mismatch (degrees)	−12.2 (12.8)	−1 (12.2)	0.002*
TPA (degrees)	5.2 (9.2)	6.2 (10.2)	0.70
TK within 20–40 degrees	20 (55.6)	20 (90.9)	0.005*
PI-LL within 10 degrees	12 (33.3)	16 (72.7)	0.004*
TPA <14 degrees	30 (83.3)	18 (81.8)	0.88
Final follow up			
Cobb angle (degrees)	13.6 (5.3)	15.1 (6.7)	0.35
TK (degrees)	26.7 (11.6)	27.9 (5.9)	0.64
LL (degrees)	61.7 (10.9)	55.6 (11.0)	0.04*
PI-LL mismatch (degrees)	−13.1 (11.5)	−10.5 (10.7)	0.39
TPA (degrees)	4.3 (8.8)	2.7 (8.9)	0.50
TK within 20–40 degrees	22 (61.1)	21 (95.5)	0.004*
PI-LL within 10 degrees	9 (25.0)	9 (40.9)	0.20
TPA <14 degrees	31 (86.1)	19 (86.4)	0.98

Data are presented as mean (SD) or n (%). *, P<0.05. TK, thoracic kyphosis; LL, lumbar lordosis; PI, pelvic incidence; TPA, T1 pelvic angle; SD, standard deviation.

surgeon contoured rods at last follow up (P=0.004) (*Table 2*, *Figure 1*). Preoperatively, 4 patients (18.2%) were in thoracic hypokyphosis and 2 patients (9.1%) in thoracic hyperkyphosis in the pre-contoured cohort whereas 7 patients (19.4%) were in thoracic hypokyphosis and 3 patients (8.3%) in thoracic hyperkyphosis in the surgeon contoured cohort. Zero patient in the pre-contoured cohort were in thoracic hypo- or hyperkyphosis postoperatively and at last follow up. However, two patients were in thoracic hypokyphosis and seven patients in thoracic hyperkyphosis postoperatively in the surgeon contoured cohort. At last follow, the surgeon contoured cohort had

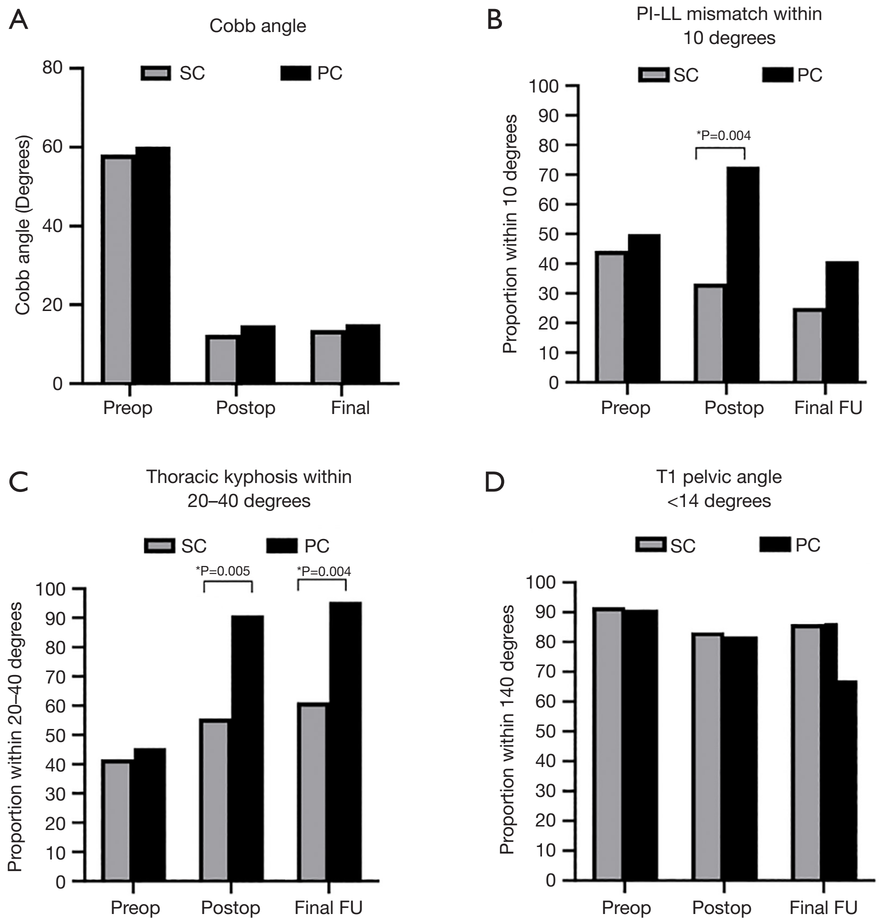

Figure 1 Preoperative, postoperative, and final follow up radiographic measurements for surgeon contoured and pre-contoured cohorts. Cobb angle measurements are shown indicating no significant difference between cohorts at all intervals (A). Proportion of surgeon contoured and pre-contoured patients with preoperative, postoperative, and final follow up PI-LL mismatch within 10 degrees (B), TK within 20–40 degrees (C) and TPA <14 degrees (D) are shown. *, P<0.05. SC, surgeon contoured; PC, pre-contoured; preop, preoperative; postop, postoperative; FU, follow up; PI, pelvic incidence; LL, lumbar lordosis; TK, thoracic kyphosis; TPA, T1 pelvic angle.

two patients that remained in thoracic hypokyphosis and four patients in thoracic hyperkyphosis.

PI-LL mismatch was within 10 degrees at initial postoperative visit in 72.7% of patients in the pre-contoured cohort *vs.* 33.3% of patients in the surgeon contoured cohort (P=0.004). However, at final follow up no statistically significant differences were seen between the cohorts with respect to PI-LL mismatch. No statistically significant differences were seen between the groups for cobb angle and TPA (*Table 2*, *Figure 1*).

Mean differences between AI predicted and observed values for the pre-contoured group were 3.7 for TK (P=0.005), 8.7 for LL (P<0.001), −7.6 for PI-LL mismatch (P=0.002), and −2.6 for TPA (P=0.11) (*Table 3*).

The cobalt chromium subgroup analysis included 20 patients in the pre-contoured cohort and six patients in the surgeon contoured cohort (*Table 4*). Immediately postoperatively 80% of pre-contoured patients achieved a PI-LL mismatch within 10 degrees compared to 16.7% in the surgeon contoured cohort (P=0.004). Ninety-five percent of pre-contoured patients met TK goal of 20–40 degrees immediately postop compared with 66.7% of surgeon contoured cohort (P=0.057). At final follow up, 100% of pre-contoured patients met TK goal compared with 66.7% of patients in the surgeon contoured cohort (P=0.007). However, only 45% pre-contoured patients met a PI-LL mismatch goal within 10 degrees at final follow up. There were no differences in TPA between the groups.

Discussion

This retrospective comparative study of AIS patients who underwent PSF demonstrates improved postoperative TK and PI-LL mismatch with utilization of pre-contoured patient-specific rods compared with surgeon contoured rods.

Table 3 Comparison of mean preoperative plan measurements with postoperative measurements in the pre-contoured cohort

Radiographic measurements	Mean (SD)	P value
Preoperative plan measurements		
TK (degrees)	31.4 (3.9)	–
LL (degrees)	55.7 (8.5)	–
PI-LL (degrees)	–8.6 (9.0)	–
TPA (degrees)	3.6 (5.9)	–
Postoperative measurements		
TK (degrees)	27.7 (6.2)	–
LL (degrees)	47.0 (10.6)	–
PI-LL (degrees)	–1.0 (12.2)	–
TPA (degrees)	6.2 (10.2)	–
Plan *vs.* postoperative difference		
TK (degrees)	3.7 (5.5)	0.005*
LL (degrees)	8.7 (8.8)	<0.001*
PI-LL (degrees)	–7.6 (9.7)	0.002*
TPA (degrees)	–2.6 (7.5)	0.11

*, P<0.05. SD, standard deviation; TK, thoracic kyphosis; LL, lumbar lordosis; PI, pelvic incidence; TPA, T1 pelvic angle.

The case shown in *Figure 2A,2B* is a representative example of a patient with a Lenke 2B curve and only 9 degrees of TK, which was postoperatively restored to a normokyphotic state following surgery with precontoured rods.

Although differences between AI predicted and observed values for the pre-contoured group were statistically significant for TK (3.7; P=0.005), LL (8.7; P<0.001), PI-LL mismatch (−7.6; P=0.002), the clinical differences were relatively small which suggests high accuracy close to target value. There was also no statistically significant difference for TPA, a global sagittal parameter (−2.6; P=0.11) (*Table 3*). This highlights the benefits of preoperative planning combined with use of adaptive spinal intelligence software. A case example of a 13-year-old female with Lenke 1 AIS curve is demonstrated in *Figure 3* and demonstrates excellent postoperative correction (*Figure 3C*) that is within the target of the preoperative plan (*Figure 3D*). Strengths of this study include assessment of global sagittal alignment and inclusion of a comparison group, which many of the studies investigating outcomes of pre-contoured rods in AIS patients lack. However, this study should be interpreted with regards to its limitations. This study was a single center study with a relatively small sample size which limits its generalizability. Our follow up period is also relatively short and there was a difference in the follow up between the two cohorts but this was not statistically significant (surgeon contoured 11.3 months *vs.* pre-contoured 9.7 months; P=0.059). In addition, although we defined an ideal TK to be between 20-40 degrees, there may be some patients outside of this range who also have an appropriate TK based on their spinopelvic parameters given target

Table 4 Radiographic outcomes of surgeon contoured and pre-contoured cohorts with only cobalt chromium rods

Outcomes	Surgeon contoured (n=6)	Pre-contoured (n=20)	P value
Immediate postop			
TK within 20–40 degrees	4 (66.7)	19 (95.0)	0.057
PI-LL within 10 degrees	1 (16.7)	16 (80.0)	0.004*
TPA <14 degrees	5 (83.3)	17 (85.0)	0.92
Final follow up			
TK within 20–40 degrees	4 (66.7)	20 (100.0)	0.007*
PI-LL within 10 degrees	1 (16.7)	9 (45.0)	0.21
TPA <14 degrees	6 (100.0)	18 (90.0)	0.42

Data are presented as n (%). *, P<0.05. Postop, postoperative; TK, thoracic kyphosis; PI, pelvic incidence; LL, lumbar lordosis; TPA, T1 pelvic angle.

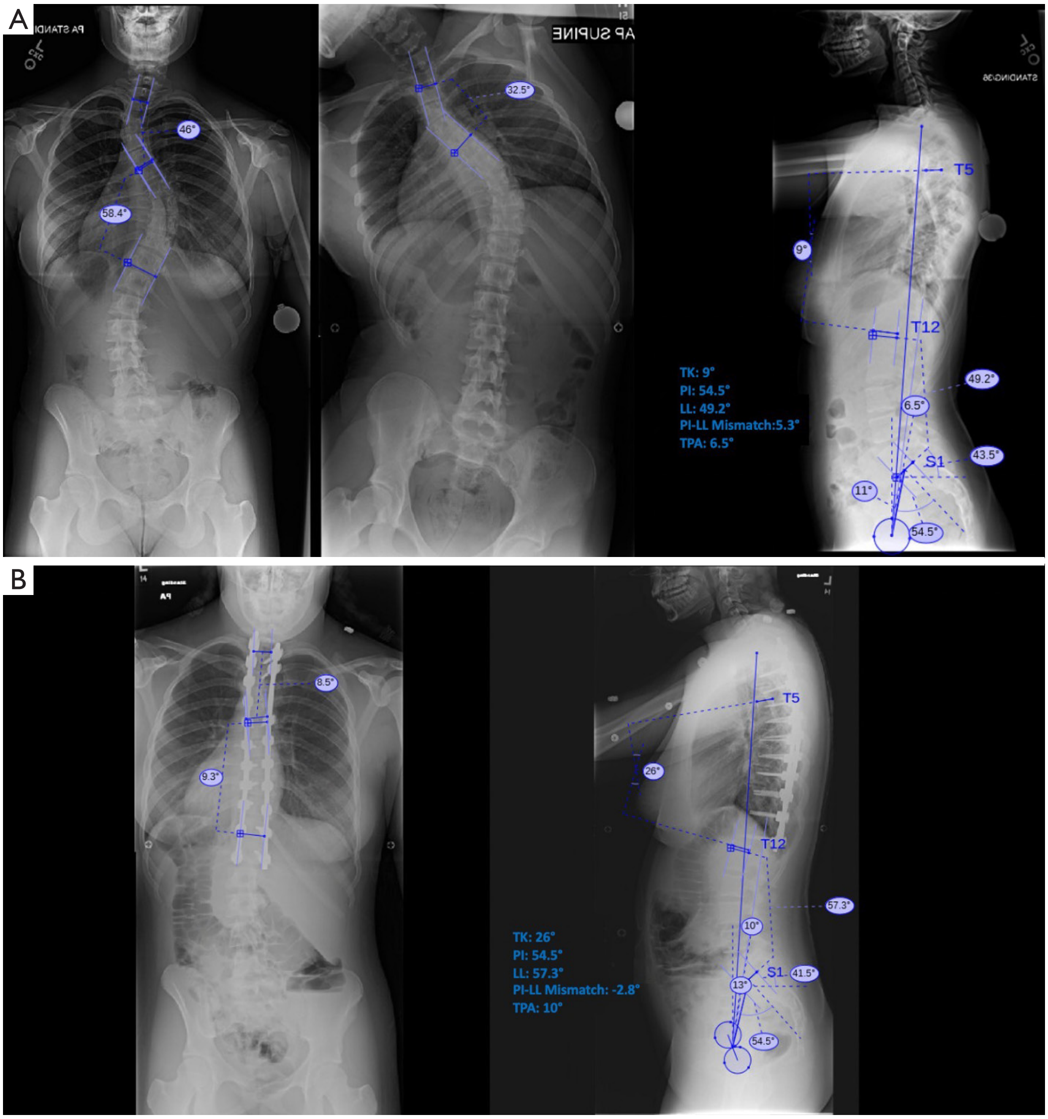

Figure 2 Pre-contoured cohort case example of a 15-year-old female with Lenke 2 AIS curve, lumbar modifier B with thoracic hypokyphosis who underwent T2–T12 PSF utilizing pre-contoured rods. Preoperative anteroposterior, anteroposterior (left-sided bending), and lateral radiographs are shown and demonstrate a 58-degree main thoracic curve, a 46-degree proximal thoracic curve which remains >25 degrees with lateral bending, and thoracic hypokyphosis (TK =9) (A). Postoperative radiographs demonstrate improved coronal alignment as well as TK (TK =26) (B). TK, thoracic kyphosis; PI, pelvic incidence; LL, lumbar lordosis; TPA, T1 pelvic angle; AIS, adolescent idiopathic scoliosis; PSF, posterior spinal fusion.

TK = 2 × (pelvic tilt + LL − PI) (20,21). However, this formula was noted to not be as accurate for patients less than 15 years old and would thus not apply to many of the patients in our study population (average age of 14 years for both cohorts). Also, we assessed T5–T12 TK but global sagittal kyphosis may be a more comprehensive measure of overall TK (21).

Another limitation is that the surgeon contoured rods were predominantly titanium whereas most of the pre-contoured rods were cobalt chromium, which could have impacted our results given the differences in Young's modulus of the materials. However, the cobalt chromium subgroup analysis demonstrated improved TK in the pre-contoured cohort which approached statistical significance

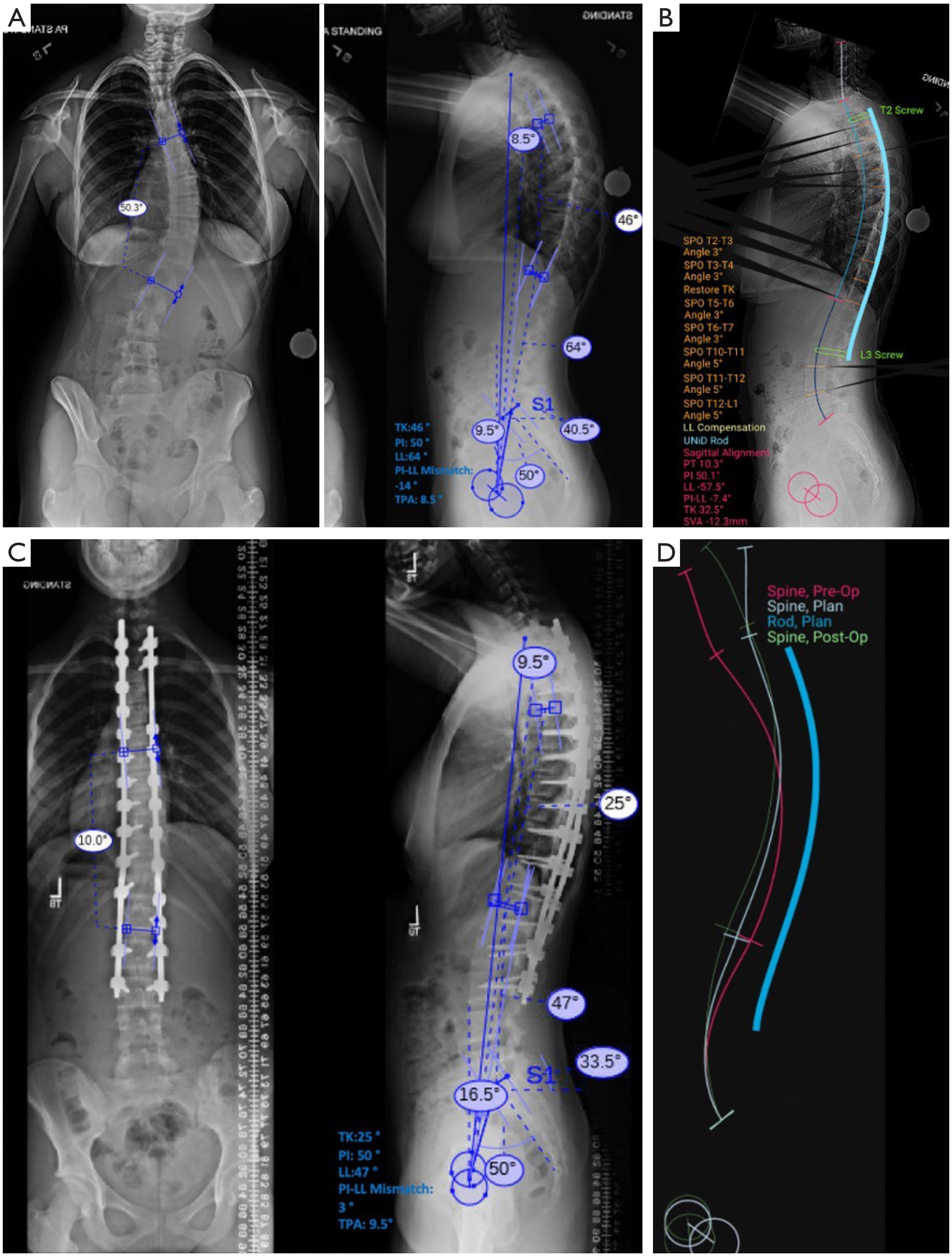

Figure 3 Pre-contoured cohort case example of a 13-year-old female with Lenke 1 AIS curve, lumbar modifier A who underwent PSF utilizing pre-contoured rods. Anteroposterior and lateral radiographs with preoperative (A), preoperative planned (B), postoperative (C), and superimposed (D) measurements demonstrating excellent postoperative correction within the target of the preoperative plan. TK, thoracic kyphosis; PI, pelvic incidence; LL, lumbar lordosis; TPA, T1 pelvic angle; SPO, Smith-Petersen osteotomy; PT, pelvic tilt; SVA, sagittal vertical axis; pre-op, preoperative; post-op, postoperative; AIS, adolescent idiopathic scoliosis; PSF, posterior spinal fusion.

immediately postoperatively (95% *vs.* 66.7%, P=0.057) and was statistically significant at last follow up (100% *vs.* 66.7%, P=0.007) when compared with the surgeon contoured cohort. The rate of achievement of a PI-LL mismatch goal within 10 degrees was also higher in the pre-contoured cohort immediately postoperatively (80% *vs.* 16.7%, P=0.004) but there was no significant difference at last follow up (45% *vs.* 16.7%, P=0.21). It is unclear why the PI-LL mismatch was not maintained at 1 year in this subset of patients but could be due to technical measurement variability as even intraobserver differences can exist (22). Other reasons include potential change in rod shape or remodeling of the LL. Nevertheless, the pre-contoured rod methodology adds an element of precise preoperative planning and patient-specific rod contouring that was previously unavailable to surgeons and patients. These results indicate that this enabling technology may reduce variability in rod contouring and optimize sagittal plane outcomes in AIS. Further study comparing outcomes between surgeon contoured and pre-contoured rods with similar materials are needed.

Few previous studies have investigated the impact of patient-specific pre-contoured rods on post-operative sagittal and coronal radiographic parameters for AIS patients undergoing PSF. Marya *et al.* carried out a non-comparative study of 61 AIS patients who were treated with the use of patient-specific rod templating and demonstrated excellent coronal plane correction and majority of patients achieved a post-operative TK within the optimal range of 20–40 degrees (17). In a prospective, non-comparative study by Solla *et al.* of 37 AIS patients who underwent PSF using pre-contoured rods, TK at last follow up was normal in all patients and close to target value (11). However, suboptimal alignment can still occur with use of pre-contoured rods as 12 patients in this study had a TK that, despite being considered normal, was undercorrected and 13 patients were overcorrected based off the preoperative plan (11).

In an institutional study of two consecutive series of 60 patients who underwent PSF for AIS using either notch-free, pre-contoured rods or conventional, manually bent rods, Sudo *et al.* demonstrated that pre-contoured rods had more optimal TK postoperatively than patients with the manually bent rods which is consistent with our study findings (23). However, this study did not investigate for potential differences in PI-LL mismatch and only had 1 week of follow up. In addition, the pre-contoured rods were not patient-specific and instead selection of rod shape was based on the level of the lowest instrumented vertebra.

Previous studies have similarly shown that AI programs are able to frequently predict postoperative radiographic parameters for patients undergoing PSF for AIS. In the study by Marya *et al.*, pre-operative planning software demonstrated high accuracy in AIS patients who underwent PSF with pre-contoured rods as they found postoperative TK to be within 5.5 degrees of the predicted value which is similar to our study finding (17). Solla *et al.* demonstrated that observed radiographic postoperative kyphosis for AIS patients was also similar to the AI predicted postoperative kyphosis (11). Similarly, in a retrospective review of a prospectively collected database of 371 patients with AIS undergoing PSF with at least 2 years of follow-up, Pasha *et al.* showed that a software model was able to predict postoperative 3D radiographic parameters with an accuracy of 75% and showed that pelvic sagittal parameters, preoperative radiographic measurements, and surgeon modifiable factors including position of upper and lower instrumented vertebrae were some of the most important predictors (24). Likewise, in the Ferrero *et al.* study of 47 AIS patients undergoing surgery using preoperative software to determine rods' shape and length, the authors found that there were no significant differences between the simulated model sagittal parameters and the postoperative radiographically measured mean sagittal parameters (25). Thus, AI is a useful tool in predicting postoperative radiographic parameters, but continued progress is needed to optimize current programs further.

In addition to improved spinal alignment with pre-contoured rods, other potential advantages include decreased surgical time and EBL (13). However, no difference in surgical time and EBL was noted in our cohort. Pre-contoured rods also minimize the notch effect as bending rods intraoperatively creates notches which may decrease its mechanical properties (26-28).

Correlation of radiographic outcomes to patient-reported outcomes (PROs) measures through tools such as Scoliosis Research Society-22 (SRS-22) questionaries is important and is an area for additional study. There have been investigations into the impact of postoperative radiographic parameters on quality-of-life metrics for patients undergoing PSF or AIS. In a retrospective review with at least 40-year follow-up of 35 patients who had undergone PSF for AIS, Rubery *et al.* demonstrated patients with a PI-LL mismatch ≤9 degrees had improved health-related quality of life (HRQoL) as noted by Oswestry

Disability Index, Patient-Reported Outcomes Measurement Information System (PROMIS) Pain Interference and Fatigue instruments compared to patients with PI-LL mismatch >9 degrees (18). Sagittal vertical axis (SVA) and pelvic tilt were not reliably associated with inferior HRQoL. However, an SVA > 50 mm was found to be associated with worse SRS-7 Scores (18). In a study of 37 patients undergoing AIS surgery with pre-contoured rods, the authors found improved postoperative compared with preoperative SRS-22 scores (4.08 *vs.* 3.61, respectively; P=0.008) (11). Conversely, in a retrospective follow-up of 98 consecutive patients who had undergone surgery for AIS with an average follow-up of 20 years, Helenius *et al.* found that neither the thoracic curve, lumbar curve, or Cobb angle or their values at the 20-year follow-up were correlated with the total SRS score (29). D'Andrea *et al.* also found little or no significant correlation between radiographic outcomes and questionnaire scores in AIS patients who underwent PSF (30). Due to the retrospective nature of our study, another limitation is lack of complete SRS questionnaire data for both cohorts and thus, PROs were not included.

Overall, this study has implications for operative management of AIS patients and will likely be of interest to surgeons considering use of pre-contoured rods to potentially improve sagittal alignment in their patients. However, as mentioned in our limitations, additional study is needed to corroborate our findings.

Conclusions

Patient-specific pre-contoured rods may help predict global sagittal balance and achieve more optimal kyphosis restoration and PI-LL mismatch than surgeon contoured rods in AIS patients undergoing PSF. Further prospective studies with larger sample sizes, long-term follow up and additional investigation of rod material impacts on postoperative alignment are needed to corroborate these findings and follow the relationship of these sagittal parameters to PROs.

Acknowledgments

This abstract was presented as an electronic ePoster at the 2024 American Academy of Orthopaedic Surgeons (AAOS) Annual Meeting and as a podium presentation at the 2024 Spine Summit Annual Meeting and 2024 European Pediatric Orthopaedic Society of North America (EPOSNA) Annual Meeting.

Funding: None.

Footnote

Reporting Checklist: The authors have completed the STROBE reporting checklist. Available at https://jss.amegroups.com/article/view/10.21037/jss-24-1/rc

Data Sharing Statement: Available at https://jss.amegroups.com/article/view/10.21037/jss-24-1/dss

Peer Review File: Available at https://jss.amegroups.com/article/view/10.21037/jss-24-1/prf

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://jss.amegroups.com/article/view/10.21037/jss-24-1/coif). D.T. receives consulting fees from Orthopediatric and DepuySynthes. He also reports Committee Membership in Pediatric Orthopaedic Society of North America and Scoliosis Research. The other authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the Institutional Review Board of Yale University (No. 2000033586) and individual consent for this retrospective analysis was waived.

References

1. Kubat O, Ovadia D. Frontal and sagittal imbalance in patients with adolescent idiopathic deformity. Ann Transl Med 2020;8:29.

2. Jada A, Mackel CE, Hwang SW, et al. Evaluation and management of adolescent idiopathic scoliosis: a review. Neurosurg Focus 2017;43:E2.
3. Illés T, Tunyogi-Csapó M, Somoskeöy S. Breakthrough in three-dimensional scoliosis diagnosis: significance of horizontal plane view and vertebra vectors. Eur Spine J 2011;20:135-43.
4. Lonner BS, Ren Y, Yaszay B, et al. Evolution of Surgery for Adolescent Idiopathic Scoliosis Over 20 Years: Have Outcomes Improved? Spine (Phila Pa 1976) 2018;43:402-10.
5. Huh S, Eun LY, Kim NK, et al. Cardiopulmonary function and scoliosis severity in idiopathic scoliosis children. Korean J Pediatr 2015;58:218-23.
6. Ghandhari H, Ameri E, Nikouei F, et al. Long-term outcome of posterior spinal fusion for the correction of adolescent idiopathic scoliosis. Scoliosis Spinal Disord 2018;13:14.
7. Abousamra O, Sponseller PD, Lonner BS, et al. Thoracic Lordosis, Especially in Males, Increases Blood Loss in Adolescent Idiopathic Scoliosis. J Pediatr Orthop 2019;39:e201-4.
8. Weiss HR, Goodall D. Rate of complications in scoliosis surgery - a systematic review of the Pub Med literature. Scoliosis 2008;3:9.
9. Jakkepally S, Viswanathan VK, Shetty AP, et al. The analysis of progression of disc degeneration in distal unfused segments and evaluation of long-term functional outcome in adolescent idiopathic scoliosis patients undergoing long-segment instrumented fusion. Spine Deform 2022;10:343-50.
10. Lonner BS, Ren Y, Upasani VV, et al. Disc Degeneration in Unfused Caudal Motion Segments Ten Years Following Surgery for Adolescent Idiopathic Scoliosis. Spine Deform 2018;6:684-90.
11. Solla F, Clément JL, Cunin V, et al. Patient-specific rods for thoracic kyphosis correction in adolescent idiopathic scoliosis surgery: Preliminary results. Orthop Traumatol Surg Res 2020;106:159-65.
12. Sardi JP, Ames CP, Coffey S, et al. Accuracy of Rod Contouring to Desired Angles With and Without a Template: Implications for Achieving Desired Spinal Alignment and Outcomes. Global Spine J 2023;13:425-31.
13. La Barbera L, Larson AN, Rawlinson J, et al. In silico patient-specific optimization of correction strategies for thoracic adolescent idiopathic scoliosis. Clin Biomech (Bristol, Avon) 2021;81:105200.
14. Solla F, Barrey CY, Burger E, et al. Patient-specific Rods for Surgical Correction of Sagittal Imbalance in Adults: Technical Aspects and Preliminary Results. Clin Spine Surg 2019;32:80-6.
15. ROAF R. Vertebral growth and its mechanical control. J Bone Joint Surg Br 1960;42-B:40-59.
16. Swarup I, Derman P, Sheha E, et al. Relationship between thoracic kyphosis and neural axis abnormalities in patients with adolescent idiopathic scoliosis. J Child Orthop 2018;12:63-9.
17. Marya S, Elmalky M, Schroeder A, et al. Correction of Thoracic Hypokyphosis in Adolescent Scoliosis Using Patient-Specific Rod Templating. Healthcare (Basel) 2023;11:980.
18. Rubery PT, Lander ST, Mesfin A, et al. Mismatch Between Pelvic Incidence and Lumbar Lordosis is the Key Sagittal Plane Determinant of Patient Outcome at Minimum 40 Years After Instrumented Fusion for Adolescent Idiopathic Scoliosis. Spine (Phila Pa 1976) 2022;47:E169-76.
19. Protopsaltis T, Schwab F, Bronsard N, et al. The T1 pelvic angle, a novel radiographic measure of global sagittal deformity, accounts for both spinal inclination and pelvic tilt and correlates with health-related quality of life. J Bone Joint Surg Am 2014;96:1631-40.
20. Clément JL, Solla F, Amorese V, et al. Lumbopelvic parameters can be used to predict thoracic kyphosis in adolescents. Eur Spine J 2020;29:2281-6.
21. Solla F, Ilharreborde B, Blondel B, et al. Can Lumbopelvic Parameters Be Used to Predict Thoracic Kyphosis at all Ages? A National Cross-Sectional Study. Global Spine J 2024;14:1116-24.
22. Loder RT, Urquhart A, Steen H, et al. Variability in Cobb angle measurements in children with congenital scoliosis. J Bone Joint Surg Br 1995;77:768-70.
23. Sudo H, Tachi H, Kokabu T, et al. In vivo deformation of anatomically pre-bent rods in thoracic adolescent idiopathic scoliosis. Sci Rep 2021;11:12622.
24. Pasha S, Shah S, Newton P, et al. Machine Learning Predicts the 3D Outcomes of Adolescent Idiopathic Scoliosis Surgery Using Patient-Surgeon Specific Parameters. Spine (Phila Pa 1976) 2021;46:579-87.
25. Ferrero E, Mazda K, Simon AL, et al. Preliminary experience with SpineEOS, a new software for 3D planning in AIS surgery. Eur Spine J 2018;27:2165-74.
26. Kokabu T, Kanai S, Abe Y, et al. Identification of optimized rod shapes to guide anatomical spinal reconstruction for adolescent thoracic idiopathic scoliosis. J Orthop Res 2018;36:3219-24.
27. Shaw KA, Devito DP, Schmitz ML, et al. Are precontoured cobalt-chromium spinal rods mechanically superior to

manually contoured rods? Spine Deform 2020;8:871-7.
28. Yamada K, Sudo H, Iwasaki N, et al. Mechanical Analysis of Notch-Free Pre-Bent Rods for Spinal Deformity Surgery. Spine (Phila Pa 1976) 2020;45:E312-8.
29. Helenius I, Remes V, Yrjönen T, et al. Comparison of long-term functional and radiologic outcomes after Harrington instrumentation and spondylodesis in adolescent idiopathic scoliosis: a review of 78 patients. Spine (Phila Pa 1976) 2002;27:176-80.
30. D'Andrea LP, Betz RR, Lenke LG, et al. Do radiographic parameters correlate with clinical outcomes in adolescent idiopathic scoliosis? Spine (Phila Pa 1976) 2000;25:1795-802.

Cite this article as: Jabbouri SS, Joo P, David WB, Jeong S, Moran J, Jonnalagadda A, Tuason D. Pre-contoured patient-specific rods result in superior immediate sagittal plane alignment than surgeon contoured rods in adolescent idiopathic scoliosis. J Spine Surg 2024;10(2):177-189. doi: 10.21037/jss-24-1