Thoracic Kyphosis Correction Using Pre-Bent Patient-Specific Rods in Adolescent Idiopathic Scoliosis: A Retrospective Analysis

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Abstract

Introduction: Adolescent idiopathic scoliosis (AIS) is a 3-dimensional congenital deformity of the spine. Current surgical treatment involves a multi-segmental posterior pedicle screw instrumentation and spinal fusion. Most reports focus on the surgical results in the coronal plane, but insufficient sagittal correction may lead to malalignment and accelerated distal segment degeneration. Currently, most surgeons contour rods based on experience during surgery without first determining the desired amount of thoracic kyphosis (TK) or measuring the angle created by the rod. In this study, we aim to determine if pre-bent patient-specific rods provide favorable sagittal alignment in AIS patients using normal reference thoracic kyphosis as our primary criteria.

Objectives: The main objective of this study was to assess whether the use of pre-bent patient-specific rods in AIS correction leads to improved sagittal alignment by achieving thoracic kyphosis angles that closely match surgically planned values. We sought to evaluate the degree of alignment across different subgroups classified by initial thoracic kyphosis and compare outcomes with normal reference kyphosis.

Methods: The study included 67 total patients. Normal thoracic kyphosis reference range was established as between 20° and 40°. Patients were then separated into different subgroups based on their initial visit thoracic kyphosis compared to the referenced range, which included hypokyphosis, normal kyphosis, and hyperkyphosis. Thoracic kyphosis was assessed at 3 separate time points via plain radiography: initial visit, pre-operative, and most recent follow-up. Surgically planned target kyphosis was determined prior to surgery and used to correct patients to the reference kyphosis range. Paired T-tests were used to analyze thoracic kyphosis between the different subgroups.

Results: Mean length to last follow-up was found to be 12.8 months. At the last follow-up, the mean increase in thoracic kyphosis was 13° for the group at large. The mean difference between kyphosis at last follow-up and target kyphosis in the subgroups was as follows: hypokyphosis was -4°, normal kyphosis was 0°, and hyperkyphosis group was +6°. Significant changes were found when comparing all subgroups' preoperative thoracic kyphosis angles with their surgical plan, and no significant differences were found when comparing their postoperative thoracic kyphosis angle with their surgical plan.

Conclusion: Prefabricated patient-specific rods achieved thoracic kyphosis angles close to surgically planned values, resulting in favorable sagittal plane alignment. The findings support the use of patient-specific rods to improve sagittal alignment and reduce the risk of malalignment and distal segment degeneration. Next steps for the study include following the cohort of patients over a longer period to assess the degree of degenerative conditions that develop in each subgroup and conducting a comparative analysis with traditional rods in all 3 anatomical planes.

Introduction

Adolescent idiopathic scoliosis (AIS) is a complex 3-dimensional spinal deformity that involves abnormal curvatures in the coronal, sagittal, and axial planes. While the primary focus of scoliosis correction has traditionally been on coronal plane realignment, abnormalities in sagittal alignment are also common and can have significant long-term consequences (1, 2). In the sagittal plane, AIS is frequently associated with thoracic hypokyphosis and lumbar hypolordosis, both of which can alter the natural curvature and biomechanics of the spine (3–6).

Postoperative hypokyphosis has been linked to trunk imbalance, potentially resulting in progressive spinal misalignment and compensatory changes in the pelvis and lower limbs (4, 6). Over time, this imbalance may contribute to early-onset osteoarthritis, disc degeneration, and chronic back pain in adulthood (4, 5). Although advancements in posterior vertebral instrumentation and fusion techniques have significantly improved the ability to achieve coronal plane correction, ensuring optimal sagittal alignment remains a challenge. Studies have reported variability in postoperative sagittal outcomes, with some patients experiencing persistent hypokyphosis or even kyphotic overcorrection, highlighting the need for more refined surgical planning and technique modifications (2–5).

As sagittal balance plays a crucial role in spinal biomechanics and long-term functional outcomes, achieving an appropriate thoracic kyphotic angle is essential for preventing postoperative complications and maintaining proper global spinal alignment. The normal range of thoracic kyphosis (TK) is generally accepted to be between 20° and 40° (8, 9). Geometric relationships have been established between pelvic incidence (PI) and lumbar lordosis (LL), as well as between TK and pelvic parameters (2–5). Achieving optimal sagittal alignment through appropriate restoration of TK is a key goal in AIS corrective surgery (1–5).

Surgeons often rely on personal experience to contour rods intraoperatively, without precisely determining the target kyphosis or measuring the rod's curvature. However, in pediatric spinal deformity surgery, the use of patient-specific, pre-bent rods has shown promising results in improving sagittal alignment (9-12). We hypothesize that patient-specific rods will closely achieve the preoperatively planned TK angles, potentially enhancing postoperative sagittal alignment and improving the rods' mechanical properties.

Methods

Study Design and Patient Selection

This study was approved by the Institutional Review Board (IRB) (20190423) and was in accordance with the ethical requirements set forth in the 1964 Declaration of Helsinki. Patients were retrospectively identified from a single tertiary care center between 2019 and 2022. The study included patients who met the following criteria: instrumentation covering at least the T4 to T12 segments, utilization of machine-bent patient-specific rods, availability of standing full-spine anteroposterior and lateral radiographs at the initial visit, preoperative evaluation, and final follow-up (minimum of 1 year), correction performed with 2 rods with high anchor density, and the use of hybrid constructs comprising pedicle screws and claw hooks.

Surgical Planning

Overall TK was defined as the maximum kyphotic curvature measured between the cranial transition vertebra (junction of TK and cervical lordosis) and the caudal transition vertebra (junction of TK and lumbar lordosis).

Target TK was determined preoperatively using radiographic measurements and PI as a reference parameter. Preoperative TK values were not used in determining the target TK (Figure 1).

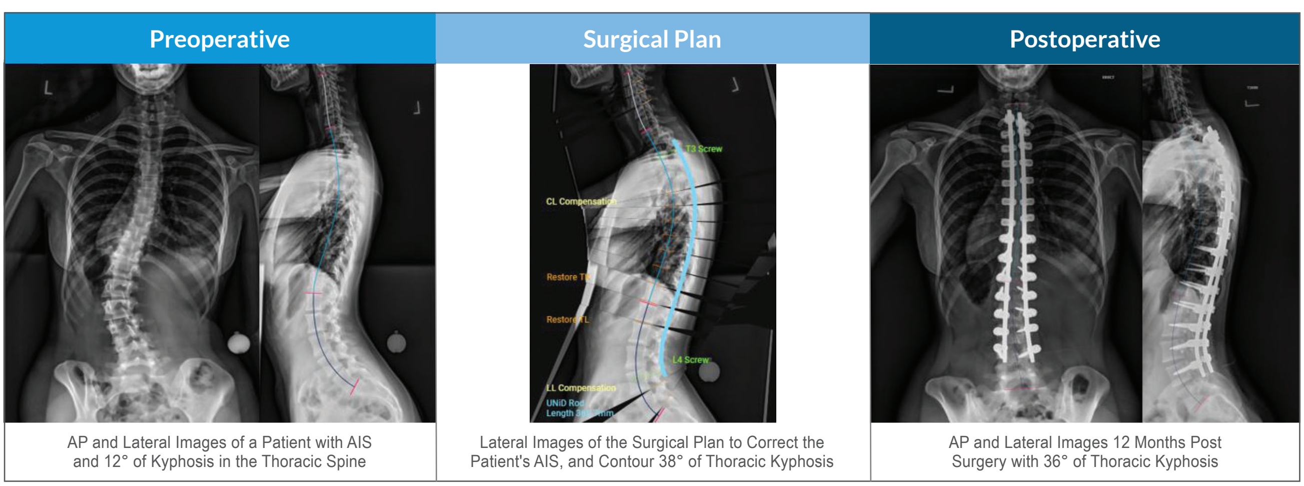

Figure 1. Preoperative, surgical plan, and postoperative radiographic images of patient with AIS and thoracic kyphosis

Subgroup Classification

To analyze outcomes, patients were categorized based on their preoperative TK values relative to the normal reference range of 20°–40°:

- Hypokyphotic (H Group) – TK < 20°
- Normal kyphosis (N Group) – TK 20°– 40°
- Hyperkyphotic (K Group) – TK > 40°

For each subgroup, the mean TK values were recorded at three time points: preoperative, surgical plan (target TK), and final follow-up (Table 1).

Assessment of Thoracic Kyphosis Changes

To evaluate the effectiveness of patient-specific rods in achieving the planned TK, the following calculations were performed for the entire cohort and each subgroup:

- Expected change in TK = Planned TK – Preoperative TK
- Measured change in TK = Final follow-up TK – Preoperative TK
- Gain difference = Expected change – Measured change. These values were analyzed to determine whether the final TK values matched the preoperative surgical targets (Table 2).

Statistical Analysis

Statistical analysis was performed using IBM SPSS Statistics v25 (IBM Corporation, Armonk, NY). Descriptive data were reported as means and ranges. Student's t-tests were used to compare within-group means (preoperative TK, planned TK, and final follow-up TK) and to assess between-group differences in TK measurements across the three subgroups. A p-value ≤ 0.05 was considered statistically significant.

Results

A total of 67 patients met the inclusion criteria and were included in the study, with a mean follow-up period of 12.8 months. The cohort was categorized into 3 subgroups based on preoperative TK: hypokyphosis (n = 21), normal kyphosis (n = 37), and hyperkyphosis (n = 9).

Mean TK values were assessed at 3 time points: preoperative, surgical plan (target TK), and postoperative. Comparison of postoperative TK with planned TK demonstrated no statistically significant differences across all subgroups (Table 1).

Preoperative vs. Planned Thoracic Kyphosis T4-T12			
Subgroup	**Preoperative Mean (°)**	**Planned Mean (°)**	**P-value**
Hypokyphotic subgroup	9.33°	37.6°	**0.0001**
Normal kyphosis subgroup	28.4°	37.8°	**0.0001**
Hyperkyphosis subgroup	48.1°	38.98°	**0.002**
Planned vs. Postoperative Thoracic Kyphosis T4-T12			
Subgroup	**Planned Mean (°)**	**Postoperative Mean (°)**	**P-value**
Hypokyphotic subgroup	37.1°	33.2°	0.08
Normal kyphosis subgroup	37.62°	38.39°	0.37
Hyperkyphosis subgroup	38.78°	44.44°	0.06

P-values ≤ 0.05 are highlighted in **bold**.
The average length to follow-up was **12.8 months.**

Table 1. Preoperative vs. Planned Thoracic Kyphosis T4-T12

Parameters	Overall Cohort (n = 67)	H Group (Hypokyphotic, n = 21)	N Group (Normal Kyphosis, n = 37)	K Group (Hyperkyphotic, n = 9)	p-value (H vs. N)	p-value (N vs. K)	p-value (H vs. K)
Expected change in TK (Plan minus pre-op)	12 (-23 to 44.2)	28 (16 to 44.2)	9 (-2 to 18)	-10 (-2 to -23)	**Eto12**	**Eto10**	**Eto12**
Measured change in TK (Post-op minus pre-op)	12 (-23.3 to 36)	24 (5.9 to 36)	9 (-2.4 to 19.1)	-4 (-23.3 to 14.8)	**Eto10**	**Eto6**	**Eto8**
Gain difference: expected gain – measured gain	0 (-16.8 to 16.5)	4 (-3.8 to 16.5)	0 (-8.7 to 9.8)	-6 (-17 to 3)	**0.002**	**0.018**	**0.0009**
T4-T12 kyphosis before surgery	26 (-6.2 to 60.6)	9 (-6.2 to 18.6)	29 (20.1 to 39.9)	49 (41.3 to 60.6)	**Eto14**	**Eto11**	**Eto12**
T4-T12 kyphosis surgical plan	38 (34.5 to 41.2)	37 (34.6 to 38.3)	38 (34.5 to 41.2)	39 (37.6 to 40.2)	0.319	**0.038**	**0.005**
T4-T12 kyphosis at last follow-up	38 (21.7 to 56.1)	33 (21.7 to 41.3)	38 (28.3 to 43.1)	45 (37.1 to 56.1)	**0.001**	**0.006**	**0.0003**

Significant p-values (≤ 0.05) are in **bold**.

Table 2. Thoracic Kyphosis and Surgical Outcomes Across Subgroups

In the overall cohort, the mean difference between planned and achieved postoperative TK was 0° (range: -16.8° to 16.5°), indicating a close match between intended and actual correction. Subgroup analysis revealed:

- Hypokyphotic group: Mean postoperative TK was 4° less than the planned correction.
- Normal kyphosis group: No difference between postoperative and planned TK.
- Hyperkyphotic group: Postoperative TK was 6° less corrected than expected (Table 2)

Discussion

This study evaluated the effectiveness of patient-specific, pre-contoured rods in achieving sagittal alignment in adolescent idiopathic scoliosis (AIS) surgery. Our findings support the hypothesis that these rods facilitate postoperative thoracic kyphosis (TK) values that closely match surgically planned targets, contributing to favorable sagittal plane correction.

Key Findings and Clinical Implications

The results demonstrate that pre-bent patient-specific rods effectively restored TK across all subgroups, with no statistically significant differences between final TK and surgical plan TK in any group. This suggests that using pre-contoured rods based on preoperative spinopelvic parameters enables precise sagittal correction, reducing the variability often seen with manually contoured rods.

Notably, the mean TK increase across the cohort was 13° at final follow-up, indicating that the rods successfully augmented kyphosis where needed. However, subgroup analysis revealed slight discrepancies in correction outcomes.

In the hypokyphosis group, postoperative TK was, on average, 4° less than the planned correction, suggesting that additional overbending or intraoperative modifications may be necessary to fully restore normal kyphosis.

The normal kyphosis group achieved near-perfect alignment, with no significant difference between planned and actual postoperative TK.

In the hyperkyphosis group, postoperative TK remained 6° higher than the planned correction, implying a potential limitation in the ability to fully reduce excessive kyphosis using pre-bent rods alone.

These findings align with prior research indicating that intraoperative rod flattening can lead to a loss of sagittal correction, particularly in hypokyphotic patients, as previously described in studies on spinal deformity correction (1, 2). The results also suggest that preoperative TK alone is not a reliable predictor of final alignment, reinforcing the importance of using PI as a key parameter in surgical planning. The incorporation of PI in preoperative assessments ensures a patient-specific approach to spinal balance, rather than relying solely on preoperative TK, which may be influenced by the scoliotic deformity.

Comparison to Traditional Rod Contouring Techniques

One of the primary challenges in AIS surgery is achieving consistent and reproducible sagittal alignment. Traditional rod contouring techniques rely heavily on surgeon experience and intraoperative estimation, often leading to unpredictable outcomes (13–16). Prior studies have reported high variability in sagittal alignment correction, with some patients experiencing postoperative hypokyphosis, which can predispose them to sagittal imbalance and degenerative changes in adulthood (12, 17–19).

In contrast, employing pre-contoured patient-specific rods provides a consistent approach to attaining the desired thoracic kyphosis angles, reducing the inconsistencies linked to manual rod contouring (11–16). The present study reinforces the notion that industrial pre-bending tailored to individual spinopelvic parameters may lead to more reproducible and predictable outcomes in AIS surgery.

Our results are consistent with prior literature demonstrating that intraoperative rod flattening can contribute to TK loss, particularly in hypokyphotic patients (16, 20). Additionally, studies comparing patient-specific rods to manually contoured rods have shown similar trends, reinforcing the benefit of preoperative planning in optimizing sagittal outcomes (12–14).

Limitations and Future Directions

This study has several limitations. First, the follow-up period (mean 12.8 months) is relatively short, limiting our ability to assess long-term stability of sagittal alignment and the potential for postoperative changes such as rod fatigue, adjacent segment degeneration, or compensatory alignment shifts. Second, the study lacks a control group of patients treated with manually contoured rods, which would provide a direct comparison to assess whether patient-specific rods truly offer superior sagittal outcomes. Third, rod material and biomechanical properties were not analyzed in this study, though these factors can influence postoperative TK maintenance.

Future research should focus on long-term follow-up studies to evaluate whether sagittal alignment is maintained over time and whether differences in alignment persist across different patient subgroups. Additionally, a comparative study with traditionally contoured rods would help determine whether patient-specific rods provide a significant advantage in sagittal plane correction. Lastly, investigating the incidence of postoperative complications, such as adjacent segment disease and revision surgery rates, could provide further insight into the long-term benefits of this approach.

Conclusion

This study demonstrates that pre-bent patient-specific rods effectively achieve sagittal alignment in AIS patients, with final TK values closely matching surgically planned targets. While minor discrepancies were observed in the hypokyphosis and hyperkyphosis subgroups, the overall cohort exhibited a mean gain difference of 0°, indicating that the intended correction was largely achieved. These findings support the continued use of preoperative planning based on PI and the application of pre-contoured rods to enhance sagittal alignment consistency. Further research is needed to explore long-term outcomes and direct comparisons with traditional rod contouring techniques.

Disclosures

Nothing to disclose.

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