Improved restoration of thoracic kyphosis using a rod construct with differentiated rigidity in the surgical treatment of adolescent idiopathic scoliosis

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OBJECTIVE The objective of this study was to compare postoperative sagittal alignment among 3 rod constructs with different rigidity profiles.

METHODS This was a dual-center retrospective cohort study involving 2 consecutive cohorts in which patients were surgically treated for adolescent idiopathic scoliosis. Lenke Type 5 curves were excluded. Patients were operated on with all-pedicle screw instrumentation using 3 different rod constructs. The first group was operated on using a hybrid construct (HC) consisting of a normal circular rod on the convex side and a beam-like rod (BR) on the concave side. The second group was operated on with a standard construct (SC) using bilateral BRs in the full length of the fusion. The third group was operated on with a modified construct (MC). The modified rods have a beam-like shape in the caudal portion, but in the cranial 2 or 3 fusion levels the rod transitions to a circular shape with a smaller anteroposterior diameter. Radiographs were analyzed preoperatively and at the first postoperative follow-up (range 1–8 weeks). The primary outcome was pre- to postoperative change in thoracic kyphosis (TK), and the secondary outcome was the ability to achieve postoperative TK within the normal range.

RESULTS The HC, SC, and MC groups included 23, 70, and 46 patients, respectively. The 3 groups did not differ significantly in preoperative demographic or radiographic parameters. The mean $\pm$ standard deviation of the preoperative main curve was $60.7^\circ \pm 12.6^\circ$, and the mean of curve correction was $62.9\% \pm 10.4\%$ with no significant difference among groups ($p \geq 0.680$). The groups did not differ significantly in coronal balance or proximal or thoracolumbar curve correction ($p \geq 0.189$). Mean postoperative TK was $23.1^\circ \pm 6.3^\circ$, $19.6^\circ \pm 7.6^\circ$, and $23.4^\circ \pm 6.9^\circ$ in the HC, SC and MC groups, respectively ($p = 0.013$), and the mean change in TK was $-3.5^\circ \pm 11.3^\circ$, $-7.1^\circ \pm 11.6^\circ$, and $0.1^\circ \pm 10.9^\circ$, respectively ($p = 0.005$). The MC group had significantly higher postoperative TK and less loss of TK compared with the SC group ($p \leq 0.018$). Postoperative TK $\leq 10^\circ$ was found in 12 patients (17%) in the SC group, 1 patient (5%) in the HC group, and 1 patient (2%) in the MC group ($p = 0.021$). There were no differences in proximal alignment, thoracolumbar alignment, or sagittal vertical axis ($p \geq 0.249$). Lumbar lordosis was $58.9^\circ \pm 11.2^\circ$ in the HC group versus $52.0^\circ \pm 1.3^\circ$ and $55.0^\circ \pm 11.0^\circ$ and the SC and MC groups, respectively ($p = 0.040$).

CONCLUSIONS In the 3 rod constructs with different rigidity profiles, significantly better restoration of kyphosis was achieved with the use of bilateral modified rods compared with bilateral standard rods. In the MC and HC groups, the rate of severe postoperative hypokyphosis was significantly lower than in the SC group. This is the first study to describe the clinical use of a rod with a reduced proximal diameter and show marked radiographic improvement in sagittal alignment.

<https://thejns.org/doi/abs/10.3171/2017.7.FOCUS17351>

KEY WORDS rod; rigidity; adolescent idiopathic scoliosis; thoracic kyphosis; sagittal alignment; construct; instrumentation

ABBREVIATIONS AIS = adolescent idiopathic scoliosis; AP = anteroposterior; BR = beam-like rod; HC = hybrid construct; MC = modified construct; PS = pedicle screw; SC = standard construct; TK = thoracic kyphosis.

SUBMITTED June 1, 2017. **ACCEPTED** July 6, 2017.

INCLUDE WHEN CITING DOI: 10.3171/2017.7.FOCUS17351.

The main purpose of the surgical treatment of adolescent idiopathic scoliosis (AIS) is to achieve a stable deformity correction while ensuring a balanced spine in the coronal and sagittal planes.¹⁰ Coronal deformity correction has improved substantially with the introduction of all-pedicle screw (PS) constructs, which largely have replaced hook-based instrumentation in modern AIS surgery.^{9,21,33,38} Numerous studies have confirmed that coronal and axial curve correction with PS instrumentation is substantial with minimal loss of correction at mid- and long-term follow-ups, resulting in significant improvement in the quality of life for the patient.^{13,15,31,35} However, to achieve a balanced spine in the 3D plane, normal sagittal balance should be the goal. AIS patients typically have relative preoperative lordosis of the thoracic spine (i.e., hypokyphosis) that should be addressed intraoperatively,²⁹ but several studies have shown that PS constructs are not efficient in restoring thoracic kyphosis (TK) to a normal range.^{25,38} The reason for this is not fully understood but is believed to be associated with intraoperative correction techniques and the biochemical properties of the rods.^{1,5,11} Various rod insertion techniques have been described to optimize 3D correction, including derotation, cantilever reduction, translation, and in situ rod bending, but none of these have shown a consistent positive effect on sagittal alignment.^{7,17,27,37}

Recently, a study assessed the effect of increasing rod strength by introducing bilateral beam-like rods (BRs), which have a larger anteroposterior (AP) diameter than traditional circular rods (Fig. 1). This resulted in improved coronal curve correction, but a loss of TK was observed postoperatively.¹² The 3D effects of increasing rod rigidity have not been firmly established, and we hypothesize that increasing the strength of the rod may have a negative effect on the sagittal profile as it can be technically challenging to achieve sufficient kyphosis of the rod while ensuring correct rod insertion and at the same time correcting the coronal deformity. A recent study, using a computerized model, showed that the use of rods with a small-diameter transition at the most cranial level results in decreased stress at the proximal junction, which may have an effect on the sagittal profile in a clinical setting.⁴

Achieving optimal sagittal alignment should be a key objective of surgery as postoperative hypokyphosis is unsatisfactory to the patient and may affect the patient's long-term quality of life.^{11,14} As such, the aim of the current study was to compare postoperative sagittal alignment among 3 rod constructs with different rigidity profiles.

Methods

The current study was a dual-center retrospective cohort study. Two consecutive cohorts that were surgically treated for AIS between September 2012 and October 2016 were included. The inclusion criteria were a diagnosis of AIS and a structural main thoracic curve (Lenke Type I, II, III, IV, and VI)²³ and all-PS instrumentation of the main thoracic curve. A subset of the population was previously described.¹² This study was approved by the local data protection agency and patient safety authority.

Surgical Technique

All patients were operated on through a posterior mid-line approach with no adjuvant anterior release. Surgical correction involved facetectomies at all levels intended for fusion, and segmental uniplanar low-profile pedicle screws were used for fixation. Differential rod contouring with rod derotation was performed, and direct vertebral rotation was applied when deemed necessary. Ponte osteotomies at the apex were not used routinely except in stiff curves evaluated intraoperatively by the surgeon. Patients were divided into 3 groups: The first group was operated on using a hybrid construct (HC) consisting of a normal circular rod on the convex side of the main curvature and a standard BR on the concave side. The second group was operated with a standard construct (SC) using bilateral BRs in the full length of the fusion. The third group was operated with a modified construct (MC). For the MC, the rods have a beam-like shape in the caudal portion, but in the cranial 2 or 3 fusion levels the rod transitions to a circular shape with a smaller AP diameter (5.5 mm) (Fig. 1). This design is believed to allow more reliable cranial contouring of the rod and less junctional stress, thus augmenting kyphosis, but this has never been examined in a clinical setting.

Radiographic Analysis

All images were uploaded to the same radiographic software (KEOPS, SMAIO), and radiographic measurements were done by 1 investigator (C.D.) with extensive experience in diagnosis of pediatric deformities. Radiographs were analyzed preoperatively and at the first postoperative follow-up, which was within the first 6 weeks after surgery. From the standing AP radiograph, the following variables were measured: the Cobb angles of the main thoracic curve, proximal thoracic curve, and thoracolumbar curve, translation of the apical vertebra, and coronal balance (the horizontal distance from the C-7 plumb line to the central sacral vertical line). On the standing lateral radiograph, the following variables were measured: TK (T5–12), lumbar lordosis (L1–S1), proximal sagittal alignment (T2–5), thoracolumbar sagittal alignment (T10–L2), and sagittal vertical axis. The Cobb angle of the main curve was measured on the preoperative supine lateral-bending radiograph. Additional variables included the curve type according to Lenke et al.,²³ number of vertebrae in the main curve, and number of fused segments. Additionally, preoperative flexibility and postoperative curve correction were calculated.

Statistical Analysis

The primary outcome was pre- to postoperative change in TK, and the secondary outcome was the ability to achieve postoperative TK within the normal range. All statistical analyses were performed using R (version 3.3.1; R Core Team). Data are presented as the percentage, mean $\pm$ standard deviation, or median with interquartile range. Data distributions were assessed with histograms, and either the chi-square test or Fisher's test was used to analyze categorical data. Parametric data were compared using the Kruskal-Wallis test or ANOVA. Post hoc analysis was

FIG. 1. Left: Standard beam-like rod. **Right:** Modified rod with a beam-like shape in the caudal portion. In the cranial 3 fusion levels, the rod transitions to a circular shape with a smaller AP diameter.

performed in cases of significant difference using Tukey's post hoc test. A *p* value of less than 0.05 was considered statistically significant.

Results

A total of 141 patients met the inclusion criteria. Two patients were excluded because of insufficient radiographic data, leaving 139 patients for the final analysis. The HC group consisted of 23 patients who were all surgically treated by the same surgeon, while the SC and MC groups consisted of 70 and 46 patients, respectively. These

patients were operated on in a consecutive manner (SC group followed by MC group) at the same facility by 1 of 5 experienced staff surgeons. All rods were 5.5-mm cobalt-chrome rods, except in the cases of 3 patients in the HC cohort in whom 4.5-mm cobalt-chrome rods were used.

The 3 groups did not differ in terms of sex or Lenke curve distribution ($p \geq 0.118$) (Table 1). The mean preoperative main curve was $60.7^\circ \pm 12.6^\circ$, and the mean curve correction was $62.9\% \pm 10.4\%$ with no significant difference among groups ($p \geq 0.680$) (Table 2 and Fig. 2). The groups did not differ significantly in terms of coronal bal-

TABLE 1. Baseline clinical and radiographic variables

Variable	Construct Group			p Value
	HC	SC	MC	
No. of patients	23	70	46	
Sex, no. (%)				
Female	20 (87)	57 (81)	40 (87)	
Male	3 (13)	13 (19)	6 (13)	0.776
Lenke type, no. (%)				
1	19 (83)	40 (57)	29 (63)	
2	1 (4)	15 (21)	7 (15)	
3	2 (9)	3 (4)	5 (11)	
4	1 (4)	4 (6)	0 (0)	
6	0 (0)	8 (11)	5 (11)	0.118
No. of vertebrae in main curve, median (IQR)	7 (7–8)	7 (6–8)	7.0 (7–8)	0.598
No. of vertebrae in fusion, median (IQR)	12 (11–13)	11 (10–12)	11 (10–12)	0.158
Main curve, °	60.1 ± 15.5	62.2 ± 12.7	58.8 ± 10.4	0.355
Flexibility of main curve, %	39.7 ± 16.7	40.7 ± 16.2	38.7 ± 14.0	0.802
Translation of main curve, cm	5.3 ± 3.1	6.4 ± 3.0	6.0 ± 25.0	0.334
Proximal curve, °	35.5 ± 11.0	37.8 ± 10.8	36.8 ± 10.8	0.682
Thoracolumbar/lumbar curve, °	28.2 ± 10.5	31.8 ± 12.1	31.5 ± 10.8	0.444
Coronal balance, median (IQR), cm*	1.7 (0.9–2.7)	1.8 (0–2.7)	1.2 (0.5–2.1)	0.965
TK, °	26.6 ± 13.8	26.2 ± 12.8	23.7 ± 12.7	0.430
Proximal alignment at T2–5, °	14.3 ± 6.8	12.4 ± 6.4	13.4 ± 6.8	0.463
Thoracolumbar alignment at T10–L2, °	7.7 ± 8.5	9.4 ± 6.8	10.7 ± 6.2	0.249
Lumbar lordosis, °	65.4 ± 10.3	58.9 ± 11.1	61.0 ± 12.0	0.067
Sagittal vertical axis, median (IQR), cm*	2.8 (1.4–5.4)	3.4 (2.0–5.6)	3.2 (1.6–4.4)	0.459

IQR = interquartile range.

Values are presented as the mean ± standard deviation unless otherwise specified.

* Absolute values are shown.

TABLE 2. Postoperative radiographic variables

Variable	Construct Group			p Value
	HC	SC	MC	
Main curve, °	21.8 ± 6.1	22.8 ± 8.3	22.1 ± 6.5	0.821
Translation of main curve, cm	14.2 ± 8.8	19.3 ± 15.0	18.7 ± 12.7	0.270
Curve correction of main curve, %	63.0 ± 9.4	63.5 ± 9.8	61.8 ± 11.9	0.680
Proximal curve, °	12.6 ± 6.2	15.8 ± 8.6	16.0 ± 7.3	0.189
Thoracolumbar/lumbar curve, °	17.5 ± 6.0	19.5 ± 7.4	18.2 ± 6.1	0.405
List, median (IQR), cm*	1.3 (1.0–1.7)	1.6 (0.8–2.4)	1.8 (0.8–3.1)	0.567
TK, °	23.1 ± 6.3	19.6 ± 7.6	23.4 ± 6.9	0.013
Kyphosis change, °	−3.5 ± 11.3	−7.1 ± 11.6	0.1 ± 10.9	0.005
Proximal alignment at T2–5, °	15.0 ± 5.7	15.5 ± 6.6	14.1 ± 6.9	0.569
Thoracolumbar alignment at T10–L2, °	7.5 ± 6.6	7.0 ± 5.7	7.9 ± 5.9	0.728
Lumbar lordosis, °	58.9 ± 11.2	52.0 ± 1.3	55.0 ± 11.0	0.040
Sagittal vertical axis, median (IQR), cm*	2.7 (1.2–4.5)	2.9 (1.7–5.2)	3.0 (1.6–5.0)	0.923

Values are presented as the mean ± standard deviation unless otherwise specified. Boldface type indicates statistical significance.

* Absolute values are shown.

ance or proximal or thoracolumbar curve correction ($p \geq 0.189$).

In the sagittal plane, the groups were similar at the preoperative stage, although lumbar lordosis was $65.4^\circ \pm 10.3^\circ$ in the HC group versus $58.9^\circ \pm 11.1^\circ$ and $61.0^\circ \pm 12.0^\circ$ in the SC and MC groups, respectively ($p = 0.067$)

(Table 1). Mean postoperative TK was $23.1^\circ \pm 6.3^\circ$, $19.6^\circ \pm 7.6^\circ$, and $23.4^\circ \pm 6.9^\circ$ in the HC, SC, and MC groups, respectively ($p = 0.013$), and the mean change in TK was $-3.5^\circ \pm 11.3^\circ$, $-7.1^\circ \pm 11.6^\circ$, and $0.1^\circ \pm 10.9^\circ$, respectively ($p = 0.005$) (Table 2 and Fig. 3). Post hoc analysis showed that the MC group had significantly higher postoperative

FIG. 2. AP and lateral radiographs of a Lenke Type 1A curve instrumented with bilateral modified rods. **Left:** The preoperative main curve was 58° with -4° TK. **Right:** Curve correction was 78%, and TK was corrected to 19° postoperatively.

FIG. 3. Preoperative to postoperative changes in TK in the patients in each of the 3 groups. Four patients did not have sufficient preoperative and postoperative imaging and their cases are not illustrated.

TK and less loss of TK compared with the SC group ($p \leq 0.018$) (Table 3). Postoperative TK $\leq 10^\circ$ was found in 12 patients (17%) in the SC group, 1 patient (5%) in the HC group, and 1 patient (2%) in the MC group ($p = 0.021$) (Fig. 4). There was no significant correlation between coronal curve correction and kyphosis change (Pearson's $r = 0.01$; $p = 0.914$), and there were no significant differences in proximal alignment, thoracolumbar alignment, or sagittal vertical alignment ($p \geq 0.249$). Lumbar lordosis was $58.9^\circ \pm 11.2^\circ$ in the HC group versus $52.0^\circ \pm 1.3^\circ$ and $55.0^\circ \pm 11.0^\circ$ in the SC and MC groups, respectively ($p = 0.040$).

Discussion

The use of a MC improved the restoration of TK by more than 7° compared with the SC group. A small loss of TK was observed in the HC group, which was not significantly different from the MC or SC group. Severe hypokyphosis (TK $\leq 10^\circ$) was found in only 1 patient in both the HC and MC groups versus 12 patients in the SC group. Fig. 3 shows that “normalization” occurred in the HC and MC groups in the sense that both large kyphosis and small kyphosis were corrected with surgery. However, in the SC group, a substantial number of patients with small preoperative TK had hypokyphosis after surgery. This is in line with previous results showing that with traditional PS instrumentation a smaller preoperative TK is the main driver of postoperative hypokyphosis.^{11,36}

While PS instrumentation provides a strong 3-column

fixation with considerable corrective power, it does have potential secondary effects in terms of imposed alignment (reduced postoperative spontaneous correction), distal and proximal junctional stress, and modifications in sagittal balance and spinopelvic alignment.³⁰ Maintenance of the sagittal profile is a controversial topic, but a recent meta-analysis concluded that the PS construct had less power to restore TK compared to a hook-and-wire construct with caudal PS,⁵ although the coronal curve was not taken into account. The insertion and contouring of the rods has been suggested as the main factor that determines sagittal alignment, and it is commonly perceived that increas-

TABLE 3. Results of Tukey's post hoc test

Post Hoc Test	p Value
TK	
Standard vs hybrid	0.118
Modified vs hybrid	0.989
Modified vs standard	0.018
Kyphosis change	
Standard vs hybrid	0.386
Modified vs hybrid	0.473
Modified vs standard	0.003

Boldface type indicates statistical significance.

FIG. 4. Distribution of postoperative TK in the 3 groups.

ing rod strength reduces intraoperative flattening, thereby ensuring retention of the precontoured rod.^{20,24} However, Prince et al. reviewed more than 1100 patients and found no evidence to suggest that increased rod strength improves TK.³² This was further underlined by Monazzam et al. who, in a multicenter review, showed no effect of rod strength in restoring TK²⁸ but found that TK restoration relied primarily on surgical technique. Our results are in line with these findings showing that a technically less challenging construct (HC or MC) can improve postoperative alignment without compromising coronal curve correction.

Patients underwent standard AP and lateral radiography, and as such the current study does not provide assessment of axial plane rotation. In a recent study, Newton et al. used biplanar slot scanners (EOS) to visualize the 3D structure of the deformity.²⁹ Newton et al. found that at the preoperative stage, TK is often overestimated on 2D radiographs and the difference between 2D and 3D TK measurements is strongly correlated with apical vertebral rotation. This, however was not the case for the postoperative assessment where the difference between the 2D and 3D radiographs was very small, likely due to surgical correction of rotation. As such, it is probable that the preoperative TK in the current study was smaller than reported and the actual loss of kyphosis was therefore overestimated. However, we would expect this variation to be distributed equally in all 3 groups, and the significant postoperative difference among groups was unlikely to be affected by apical rotation as this is largely corrected during surgery.

The clinical importance of reduced postoperative kyphosis has yet to be elucidated, and clinically relevant thresholds have not been established. The Lenke classification considers TK of 10°–40° to represent a normal range,²³ while others consider TK of 10°–20° to be mild hypokyphosis.^{8,26} More than 25% of patients in all 3 groups of our study population had mild hypokyphosis according to this definition (Fig. 4), but, irrespective of

the definitions, the long-term effect of postoperative hypokyphosis on patient-reported outcomes is still unknown. Postoperative hypokyphosis is unlikely to affect the patient's quality of life at early or midterm follow-up because AIS patients exhibit a range of compensatory mechanisms and rarely become decompensated.^{2,3,22} However, in adult spinal deformity patients, several studies have shown that an optimal sagittal profile is essential to avoiding pain and disability,^{16,34} and, as such, a primary objective of AIS surgery should be to achieve an optimally aligned spine to ensure long-term quality of life.

Patients in the SC and MC groups were operated on at the same tertiary facility by a small dedicated group of surgeons, whereas patients in the HC group were operated on at a different facility by a single surgeon (J.A.I.F.). To ensure that our results were not affected by unrecognized differences in surgical technique, J.A.I.F. and M.G. performed several AIS procedures in conjunction prior to the initiation of the study. The homogeneity of the groups was further underlined by the similarities in the postoperative coronal parameters, including similar curve correction, global balance, and fusion length (Table 2). However, as with any multicenter study, our results are potentially influenced by local differences in surgical factors, which is a limitation to our study.

The clinical use of a differentially shaped rod with a reduced proximal diameter has not been previously described. As such, this study was designed as a proof of concept and 2-year follow-up data are not included, which is a limitation to the clinical applicability of our findings. Previous studies have shown that TK remains stable after PS instrumentation, but a small increase (0°–4°) can be expected after 2 years.^{6,18,19} The lack of midterm follow-up data does not, however, affect the biomechanical interpretation of our findings, and our data support the notion that a modified rod construct with a diameter transition can improve sagittal alignment after surgical treatment of AIS. Although the BR design is not universally used, we hypothesize that the principles of the diameter transition

rod can be transferred to other designs, and we would encourage future studies to verify this assumption.

Conclusions

In the 3 rod constructs with different rigidity profiles, we found significantly better restoration of kyphosis with the use of bilateral modified rods compared with bilateral standard rods. In the MC and HC groups, the rate of severe postoperative hypokyphosis was significantly lower than in the SC group. This is the first study to describe the clinical use of a rod with a reduced proximal diameter and show marked radiographic improvement in sagittal alignment. Future studies should address the long-term clinical implications of this improvement.

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Disclosures

Drs. Ohrt-Nissen, Gehrchen, and Dahl received an institutional grant from K2M unrelated to the submitted work. Drs. Gehrchen and Dahl received an institutional grant from Medtronic unrelated to the submitted work. Dr. Ferguson is a consultant for K2M and has a nonfinancial relationship with SRS.

Author Contributions

Conception and design: all authors. Acquisition of data: Ohrt-Nissen, Dragsted. Analysis and interpretation of data: Ohrt-Nissen, Gehrchen. Drafting the article: Ohrt-Nissen. Critically revising the article: all authors. Reviewed submitted version of manuscript: Ohrt-Nissen, Dragsted, Dahl, Gehrchen. Approved the final version of the manuscript on behalf of all authors: Ohrt-Nissen. Statistical analysis: Ohrt-Nissen. Administrative/technical/material support: Ferguson, Gehrchen. Study supervision: Dahl, Ferguson, Gehrchen.

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