European Spine Journal (2019) 28:3066–3075
https://doi.org/10.1007/s00586-019-06093-z

ORIGINAL ARTICLE

A critical thoracic kyphosis is required to prevent sagittal plane deterioration in selective thoracic fusions in Lenke I and II AIS

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Received: 16 January 2019 / Revised: 29 April 2019 / Accepted: 31 July 2019 / Published online: 6 August 2019

Abstract

Purpose Thoracic hypokyphosis following AIS correction may be associated with reduced lumbar lordosis with potential adverse effects on the global sagittal balance. In the present study, we were interested in how the amount of thoracic kyphosis influences the sagittal profile and balance in selective thoracic (STF) and thoracolumbar fusions.

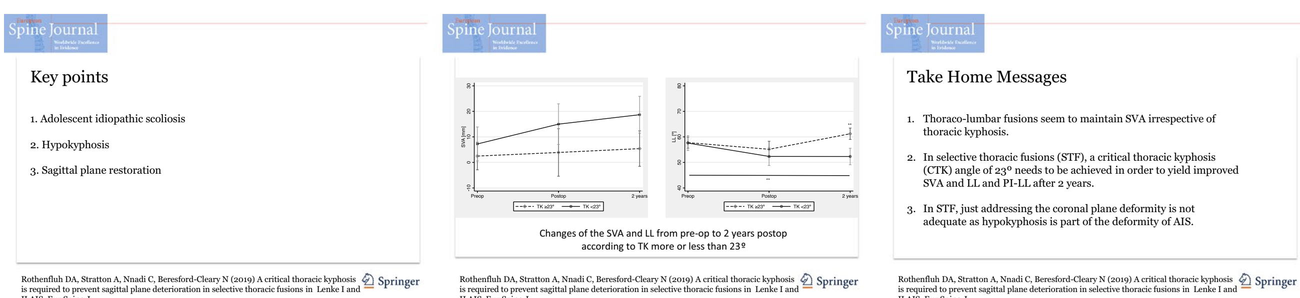
Methods Out of 154 patients, 86 patients had correction of AIS Lenke I or II with a side-loading pedicle screw system and completed a 2-year follow-up. Patient factors such as age, Risser grade, lowest and upper instrumented vertebra, and lumbar modifier were recorded. Coronal Cobb and sagittal parameters were measured using Surgimap. Statistical analysis according to distributions and multiple linear and logistic regressions was performed using STATA for Mac v13.

Results In STF, logistic regression against post-operative change in SVA versus thoracic kyphosis allowed calculation of a critical thoracic kyphosis of 23° (ROC AUC 0.65, spec 0.70, sens 0.63), below which deterioration of the sagittal vertical axis is more likely (PPV 71.4%). Patients with hypokyphosis exhibited an increase in the SVA (pre-operative 7.2 ± 37.1 mm vs. 23.1 ± 27.6 mm at 2 years, $p = 0.0164$), whereas it was maintained from pre-operative to 2 years post-operative if thoracic kyphosis is above 23° (pre-operative 2.5 ± 28.9 mm vs. 5.4 ± 26.9 mm at 2 years, $p = 0.579$).

Conclusion A critical thoracic kyphosis of 23° and more should be aimed for in hypokyphotic patients to potentially avoid post-operative sagittal plane deterioration with mechanical and likely also clinical consequences.

Graphic abstract

These slides can be retrieved under Electronic Supplementary Material.



Keywords Adolescent idiopathic scoliosis · Hypokyphosis · Sagittal plane · Thoracic kyphosis

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00586-019-06093-z) contains supplementary material, which is available to authorized users.

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Introduction

The traditional objective for correction of adolescent idiopathic scoliosis (AIS) has been to correct the coronal plane deformity. The goals of surgery were to prevent further progression of the deformity and achieve a cosmetically pleasing result by balancing the trunk and levelling the shoulders [1, 2]. But following the observation that flattening of the sagittal profile with posterior distraction devices may lead to pain and disability in later life [3], reports in recent years have investigated how coronal plane correction affects the sagittal plane [4–7].

Thoracic hypokyphosis leading to malalignment in the sagittal plane after correction of AIS has been implicated and related to several problems during follow-up. It has long been suggested that a positive sagittal balance is significantly contributing to low back pain following scoliosis surgery and up to 15% of patients were reported to have occasional or frequent low back pain [8]. The long fusion related to scoliosis correction has been related to mechanical overload of the unfused segments, and consequently early degenerative changes in the subjacent discs have been observed and reported [9, 10]. In particular, post-operative spino-pelvic incongruence has been reported to result into changes in the disc hydration patterns following AIS surgery [4] and higher rates of disc degeneration have been observed [11].

Post-operative hypokyphosis in the thoracic spine leading to spino-pelvic incongruence is expected to result into junctional adaptions or reciprocal changes above and below the fusion. Distal junctional kyphosis has been observed in up to 14.6% after posterior correction, whereas the rate following anterior correction was less [12]. Similarly, thoracic hypokyphosis has been shown to result into a loss of lumbar lordosis as a result of reciprocal change [6, 7], whereas this effect was not observed following anterior thoracic correction of AIS resulting into a post-operative increase in thoracic kyphosis [7]. A recent study further found abnormal post-operative proximal junctional kyphosis in Lenke 1 curves in relation to a loss of thoracic kyphosis and suggested a 7% higher risk for each degree of thoracic kyphosis lost [13]. These junctional reciprocal changes further highlight the relevance of the sagittal plane and its putative role in pre-operative planning for surgical correction of AIS.

Given the pertinent literature, the goals of correction should therefore also include the sagittal and not just the coronal plane. However, previous studies seem to have used an arbitrary cut-off to differentiate between thoracic hypo- and normokyphosis in AIS patients [6, 11] or have not measured or reported changes in global sagittal balance in relation to the thoracolumbar alignment [6, 7]. In the present study, we sought to use a case–control approach which would then allow the calculation of a cut-off value for the thoracic kyphosis below which sagittal plane deterioration seems more likely and which can be factored in when establishing the surgical plan.

Methods

Out of 836 cases with a scoliosis code from 2009 to 2013 in the hospital coding database, we identified 154 cases with adolescent idiopathic scoliosis which had a routine 2-year follow-up with a whole spine X-ray and were between 12 and 17 at the time of their surgery. In addition, they were included if a side-loading pedicle screw system was used in order to reduce variation in surgical technique as much as possible. Out of these, 86 had a Lenke type I or II curve with adequate lateral whole spine plain films to measure spino-pelvic parameters. Bending films were not considered in this study as the objective was to assess the sagittal plane rather than its effect on coronal correction and curve flexibility. In all cases, a posterior instrumentation of the curve was performed with a side-loading pedicle screw system to correct the coronal curve using a sliding and cantilever technique with a 6-mm titanium rod. None of the patients had 100% screw density, and all screw constructs were pedicle screws only without hybrid constructs. Patients with a scoliosis other than adolescent idiopathic were excluded. Adult patients aged 18 or more years at the time of their surgery were also excluded as their curves tend to be stiffer and curve behaviour would be different. All cases were grouped according to the lowest instrumented vertebra (LIV). Fusions stopping at L1 or above were assigned to the selective thoracic fusion (STF) group, and if the LIV was below L1, they were assigned to the thoracolumbar fusion (TLF) group.

All whole spine plain films anteroposterior and lateral were analysed using Surgimap for Mac (Nemaris, New York). The sagittal parameters were measured using the sagittal alignment (SA) tool with specifically the thoracic kyphosis being measured along the endplates of the vertebrae included in the kyphosis much rather than from T1 to T12, i.e. the separation of lumbar lordosis to thoracic kyphosis defined by the inflection point rather than T12 and L1. As reported in the tables, the C7 sagittal vertical axis (C7 SVA), pelvic incidence (PI), pelvic tilt (PT), sacral slope (SS), lumbar lordosis (LL) and thoracic kyphosis (TK) were measured in the immediate pre-operative, first immediate post-operative and 2-year follow-up X-rays. Data were exported to Microsoft Excel for further analysis.

Statistical analysis

Descriptives were calculated and analysed. Normality of data was probed using the Shapiro–Wilk's test. Comparison of means was performed using a *t* test according to distributions. In order to determine factors contributing to sagittal plane variation, multiple linear regression was performed. A categorical variable was introduced for STF based on an SVA change of equal or more than 20 mm from immediately post-operatively to 2-year follow-up. Logistic regression was performed to find determinants of SVA deterioration in STF and calculate the probability cut-off using a custom script in Stata. All statistical analyses and graphing were performed using Stata 13 for Mac (StataCorp LP, College Station, Texas). All p values reported are 2-tailed and significant if less than 0.05.

Results

Comparison STF and TLF

Out of the 86 cases analysed, there were 37 female and 5 male cases in STF (n STF = 42), whereas in TLF 38 female and 6 male cases were included (n TLF = 44). The average age at the time of surgery was 14.7 ± 1.6 and 14.7 ± 1.7 years for STF and TLF, respectively. All patients had a minimum 2-year follow-up, and the average was 2.4 ± 0.7 years in STF and 2.8 ± 1.0 years in TLF. In both groups, 38 patients had a Lenke I curve. In the selective thoracic fusion group (STF), the LIV distribution was 1 patient with LIV at T11, 16 at T12 and 26 at L1. The LIV distribution in the thoracolumbar fusion (TLF) group corresponded to 18 patients with LIV at L2, 16 at L3 and 10 at L4. The distribution of Risser grades was similar between the two groups. For Risser grades 0–2, there were 25 in the STF group and 23 patients in the TLF group. For Risser grades 3 and 4, 17 were found in the STF group and 21 patients in the TLF group. All descriptive data are presented in Table 1.

Baseline, post-operative and 2-year coronal and sagittal data are given in Tables 2 and 3. While overall the two groups are very similar and comparable, the main differences between the STF and TLF groups are the bigger Cobb angle of the main thoracic curve in the TLF group and the difference in the SVA. In the TLF group, the Cobb angle of the main thoracic curve was bigger at all time points and the Cobb angle of the minor compensatory lumbar curve was bigger pre-operatively only (data given in Table 2). The larger curve magnitude of the main as well as compensatory curve has prompted the operating surgeon to choose a thoracolumbar fusion rather than a selective thoracic fusion. Bending films were not considered in this study. The STF group had a significantly greater value for the SVA indicating a more anterior offset of the C7 plumbline at 2-year follow-up compared to TLF in which the SVA indicates a more balanced sagittal profile (STF 13.7 ± 28.3, TLF −5.9 ± 28.1, $p = 0.022$, t test, two-tailed).

Table 1 Descriptive data of patient groups

	STF (n = 42)	TLF (n = 44)
Female/male	37:5	38:6
Age at surgery (years)	14.7 ± 1.6	14.7 ± 1.7
Follow-up (years)	2.4 ± 0.7	2.8 ± 1.0
Lenke I		
A	16	13
B	9	10
C	13	15
Lenke II		
A	2	3
B	2	0
C	0	3
Risser grade		
0	11	10
1	9	6
2	5	7
3	4	1
4	13	20
LIV		
T11	1	
T12	16	
L1	26	
L2		18
L3		16
UIV		
T1	1	
T2	4	8
T3	13	21
T4	25	15

Regression analysis

In Lenke I and II curves, the deformity is corrected in the thoracic spine and correction will also affect the sagittal plane. Therefore, the relationship between the thoracic kyphosis and the SVA was further examined. Linear regression analysis revealed a negative relationship between the thoracic kyphosis and the SVA as the dependant ($p = 0.03$, $r^2 = 0.13$) as shown in Fig. 1a. A positive relationship between the thoracic kyphosis and lumbar lordosis was confirmed ($p = 0.003$, $r^2 = 0.28$) which was the much stronger relationship (Fig. 1b).

Linear regression of the change in lumbar lordosis against the change in thoracic kyphosis yields a regression coefficient of 0.67 ($p = 0.001$, $r^2 = 0.33$). This means that for every change in thoracic kyphosis of 3° a corresponding change of the lumbar lordosis of 2° can be expected which corresponds to the slope of the regression line seen in the graph in Fig. 1b.

Table 2 Baseline, postop and 2-year coronal parameters (mean ± standard deviation in [°], *t* test, 2-tailed)

	Major preop	Major postop	Major 2 year	Minor preop	Minor postop	Minor 2 year
STF	50.8 ± 10.4	23.6 ± 9.9	25.5 ± 9.1	36.1 ± 11.6	18.4 ± 5.8	8.7 ± 10.8
TLF	63.6 ± 13.8	33.2 ± 14.4	35.0 ± 13.7	44.4 ± 15.0	21.8 ± 11.6	13.3 ± 15.5
p	**0.000**	**0.000**	**0.000**	**0.047**	0.284	0.154

p values in bold are statistically signficiant with $p < 0.05$

Table 3 Baseline, postop and 2-year sagittal parameters (mean ± standard deviation all in [°] except for SVA [mm], *t* test, 2-tailed)

	SVA pre	SVA post	SVA 2 years	TK pre	TK post	TK 2 years	LL pre	LL post	LL 2 years
STF	4.5 ± 32.5	9.0 ± 38.5	**13.7 ± 28.3**	18.6 ± 11.1	19.1 ± 9.0	23.4 ± 9.7	− 57.7 ± 11.4	− 53.8 ± 14.9	− 56.9 ± 12.8
TLF	3.6 ± 29.1	11.6 ± 29.2	**− 5.9 ± 28.1**	24.0 ± 14.3	18.6 ± 10.0	21.4 ± 11.1	− 60.0 ± 15.6	− 53.0 ± 14.6	− 60.5 ± 13.7
p	0.894	0.730	**0.022**	0.053	0.849	0.385	0.416	0.818	0.232

PT pre	PT post	PT 2 years	PI
8.1 ± 7.4	9.8 ± 8.5	9.2 ± 8.5	54.1 ± 12.9
8.5 ± 9.1	10.8 ± 8.2	8.3 ± 8.9	53.0 + 13.9
0.828	0.578	0.637	0.718

p values in bold are statistically signficiant with $p < 0.05$

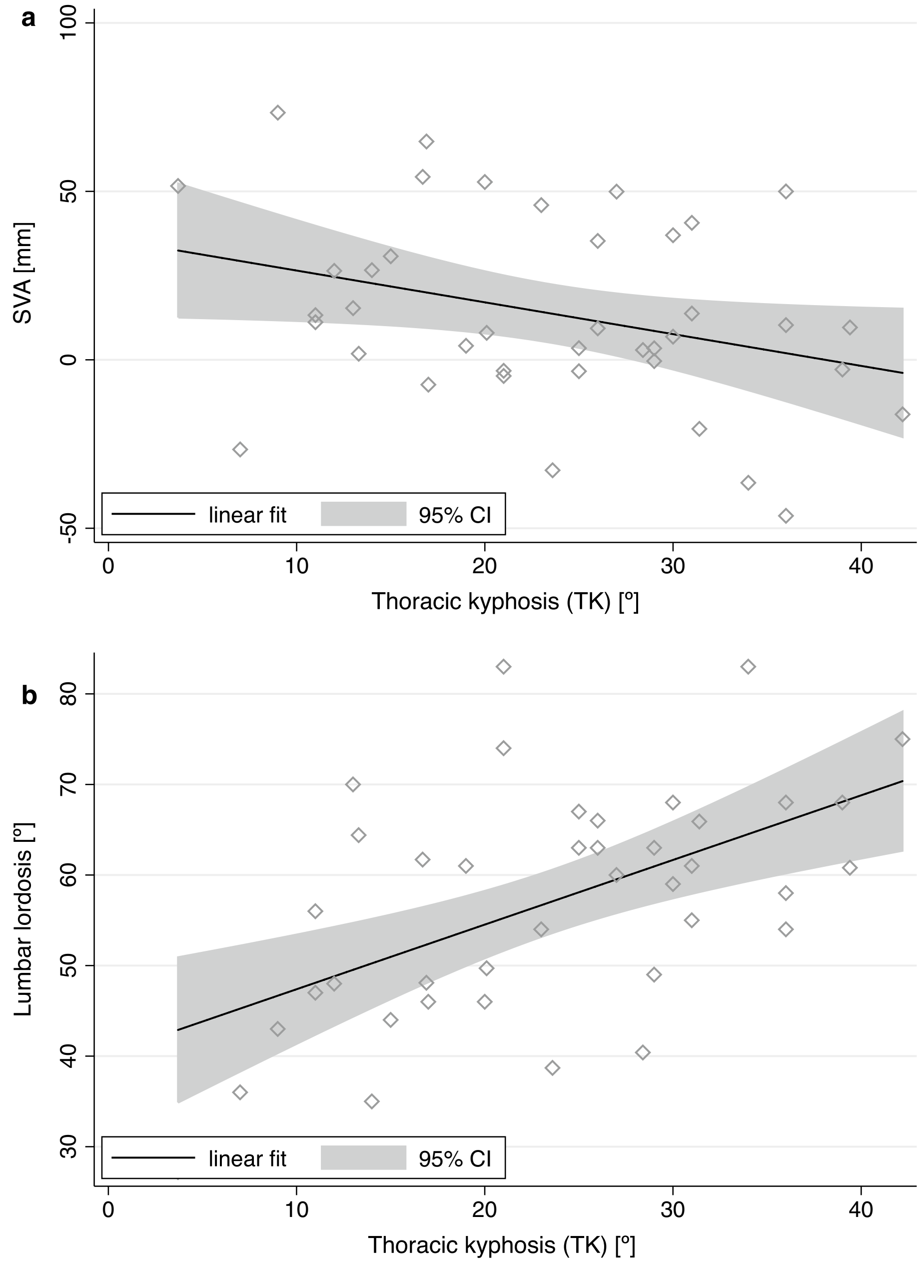
Based on the difference in SVA at 2 years post-operatively in STF vs. TLF, patients in the STF group were examined for a change in the SVA in the post-operative period and grouped into two subgroups according to an SVA change of more than 20 mm. This allowed comparison of patients with STF and SVA deterioration against patients with STF and no deterioration of the SVA during follow-up. Logistic regression was then carried out with SVA change as a function of the thoracic kyphosis ($p = 0.025$). A probability cut-off value at 23° was calculated below which sagittal plane deterioration in terms of an increase in the SVA is more likely. The area under the ROC curve (AUC) was 0.65, the sensitivity 0.70, and specificity 0.63. A positive predictive value of 71.4% was calculated.

Patients with selective thoracic fusions are subgrouped according to the critical thoracic kyphosis angle of 23° into patients with more than 23° (CTK) and less or equal than 23° (HYPO) post-operatively. The difference in SVA between HYPO and CTK was not significant at baseline (7.2 ± 37.1 mm vs. 2.5 ± 29.0 mm, $p = 0.641$). Comparing the SVA over time reveals a deterioration of the SVA from pre-operative to 2 years post-operatively in the HYPO group (pre-operative 7.2 ± 37.1 mm vs. 23.1 ± 27.6 mm at 2 years, $p = 0.0164$), whereas in the CTK group the SVA was largely maintained (pre-operative 2.5 ± 29.0 mm vs. 5.4 ± 26.9 mm at 2 years, $p = 0.579$). The difference in the SVA at 2 years between CTK and HYPO is significant ($p = 0.047$) as shown in Fig. 2a. Correspondingly, the anterior shift of the SVA is accompanied by a loss in lumbar lordosis in the HYPO group at 2 years compared to pre-operatively (pre-operative 57.6° ± 12.7 vs. 2 years 52.3° ± 14.1, $p = 0.032$). In the CTK group, there is an improvement of the LL at 2 years; however, this is not statistically significant (pre-operatively 57.8° ± 10.6 vs. 2 years 61.2° ± 10.2, $p = 0.150$). Yet, the difference in lumbar lordosis between the CTK and the HYPO group at 2 years is significant (HYPO 52.3° ± 14.1 vs. CTK 61.2° ± 10.2, $p = 0.026$) and possibly also clinically relevant with a 9° difference between the two groups in this young patient population (Fig. 2b). While stratification of the CTK cut-off value according to pelvic incidence was not possible due to the number of STF patients, comparing the PI between the CTK and HYPO group shows that patients in the CTK group have a lower PI (HYPO 59.4 + 11.2 vs. CTK 49.8 ± 13.0, $p = 0.014$) and greater PI-LL mismatch already pre-operatively which increases over time (data shown in Table 4). A logistic regression model based on TK and PI produced a valid model ($\chi^2 = 6.4$, $p = 0.041$), yet the coefficient for PI was not a significant contributor ($p = 0.204$) as opposed to TK ($p = 0.027$). Nevertheless, the finding that HYPO patients had a higher PI still highlights the importance of spino-pelvic congruence.

Discussion

The need for including the sagittal plane in analysis and surgical planning for surgery for AIS has been increasingly established over the past years. Just recently, Abelin-Genevois et al. [14] proposed a sagittal plane classification for AIS. However, in contrast to AIS the assessment of the sagittal plane in adult spinal deformity is well defined and standardised with known key spino-pelvic parameters which

Fig. 1 Linear regression analysis showing **a** a negative relationship between thoracic kyphosis (TK) and the sagittal vertical axis (SVA) and **b** a positive relationship between TK and lumbar lordosis (LL)



have been defined by either correlating the sagittal deformity to pain and disability [15, 16] or mechanical failure [17]. Patients with AIS are often hypokyphotic, and according to Somerville who described the single curve as a rotational lordosis [18], the hypokyphosis should be considered as part of the deformity. While the need for sagittal plane restoration in AIS by creating an adequate amount of thoracic kyphosis seems undisputed [11, 19], the precise amount of thoracic kyphosis required seems to be unknown or have been chosen arbitrarily.

The reciprocal change induced by post-operative hypokyphosis in the sagittal plane has been observed in several studies before. Our results indicate that in patients in which a thoracolumbar fusion was carried out, reciprocal change in the non-fused lumbar segments did not occur which prevented sagittal plane deterioration in terms of an anterior shift of the SVA irrespective of the amount of thoracic kyphosis. In patients with selective thoracic fusions, the present study did find a progressive anterior shift of the SVA at 2-year follow-up, which is consistent with earlier studies. Newton et al. [7] observed that patients which had anterior correction of the thoracic curve had more thoracic kyphosis which translated into an increased lumbar lordosis during follow-up. On the contrary, posterior correction of the thoracic curve did not restore thoracic kyphosis and resulted into a loss of the lumbar lordosis. This descriptive

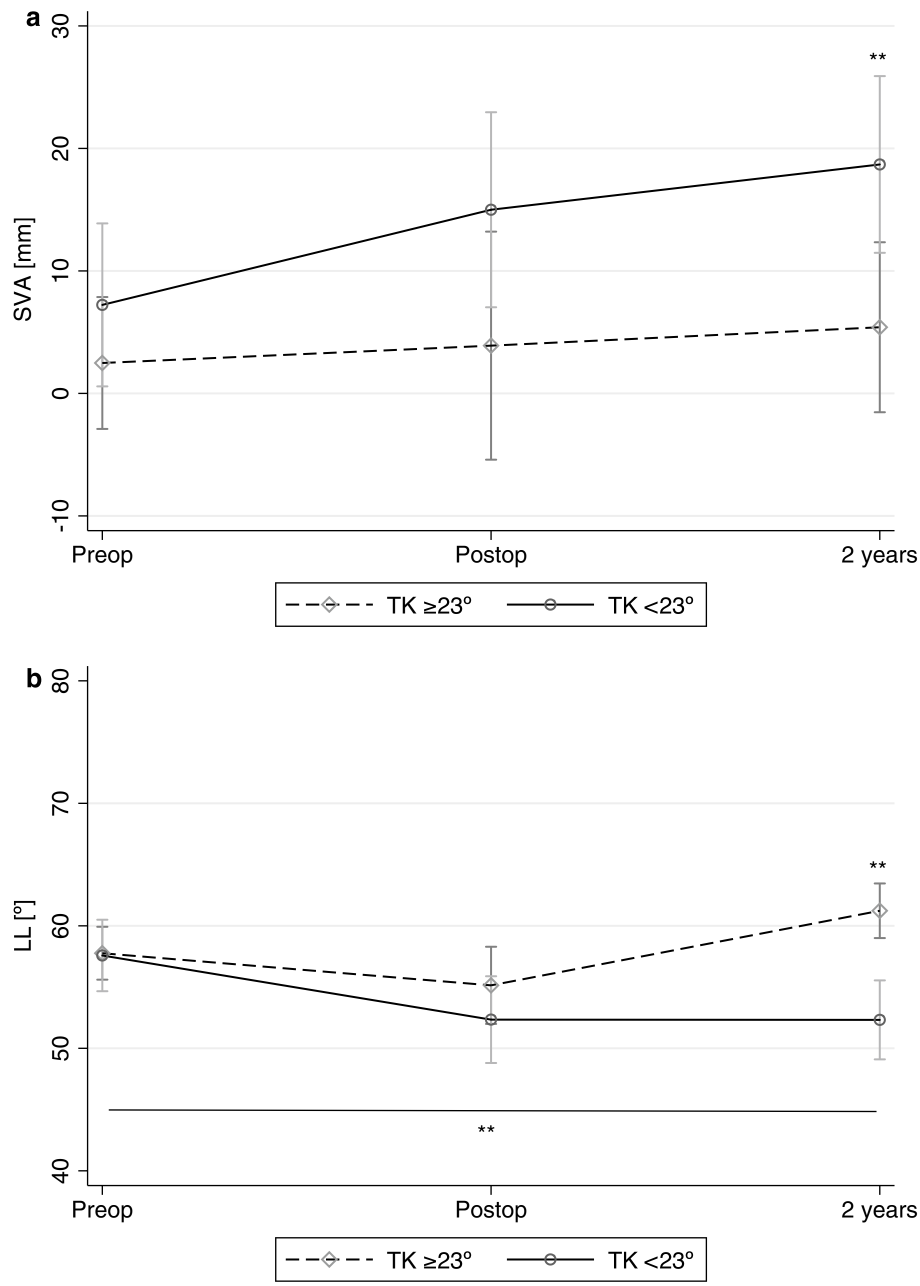


Fig. 2 Changes in **a** the sagittal vertical axis (SVA) and **b** lumbar lordosis (LL) from pre-operatively to 2 years post-operatively based on whether a critical thoracic kyphosis (CTK) of more than 23° was achieved or not

and comparative study did not attempt to establish a cut-off amount of kyphosis to prevent flattening of the lumbar spine. Matsumoto et al. [6] reported a negative correlation between the thoracic kyphosis and the SVA. The lower the kyphosis the higher and more anterior the SVA was measured with a concomitant decrease in lumbar lordosis, which is consistent with our findings. Based on this, we chose to group the patients into groups with and without SVA deterioration at 2-year follow-up and sought to establish a minimum value for post-operative thoracic kyphosis below which sagittal plane deterioration seems to occur more likely and therefore can guide surgical planning and defining the anatomic goals of surgery beyond coronal plane correction. In the present study, we calculated a critical thoracic kyphosis (CTK) of 23° below which sagittal plane deterioration seems more likely in selective thoracic fusions in Lenke I or II curves. Figure 3 shows two examples of sagittal profiles of patients in the HYPO and CTK groups, illustrating how the flat thoracic kyphosis induced a loss of lordosis and subsequent anterior shift of the SVA. Clement et al. [20] recently reported improvement of the LL of 8° in patients in which normokyphosis was restored, indicating that restoration of thoracic kyphosis can reverse or result into a positive reciprocal change. In the present study, we measured an improvement of the LL in patients with normokyphosis above 23°; however, this finding was not significant.

Table 4 Spino-pelvic parameters in STF grouped into HYPO and CTK from baseline to postop and 2 years

	PI	SVA pre	SVA post	SVA 2 years	PI-LL pre	PI-LL post	PI-LL 2 years	LL pre	LL post	LL 2 years
HYPO	59.4 + 11.2	7.2 ± 37.2	15.0 ± 41.1	23.1 ± 27.6	1.9 ± 9.2	7.1 ± 15.6	7.1 ± 12.6	−57.6 ± 12.7	−52.3 ± 15.4	−52.3 ± 14.1
CTK	49.8 ± 13.0	2.5 ± 29.0	3.9 ± 36.4	5.4 ± 26.9	−8.2 ± 11.6	−5.6 ± 15.3	−12.0 ± 15.8	−57.8 ± 10.6	−55.1 ± 14.8	−61.2 ± 10.2
p	**0.014**	0.641	0.365	**0.047**	**0.003**	**0.012**	**0.000**	0.959	0.557	**0.026**

p values in bold are statistically signficiant with $p < 0.05$

Yet, the analysis of the sagittal plane in AIS patients can not just rely on measurement of TK. As shown in Table 4, patients in the HYPO group which exhibited a deterioration of the sagittal plane had both a higher PI and greater PI-LL mismatch, indicating that they had greater spino-pelvic incongruence from the outset, which may predispose them to deterioration of the SVA and PI-LL, especially if they are selectively fused in hypokyphosis. This feature is worth noting, and the importance of addressing hypokyphosis seems to increase with increasing PI. However, in the present analysis we did not have enough patients to calculate a PI-based minimal TK to prevent sagittal plane deterioration.

The loss of lumbar lordosis has mechanical consequences on the intervertebral discs as evidenced by differences in the extent of degenerative changes. Bernstein et al. [11] established a relationship between the thoracic kyphosis and lumbar disc degenerative changes. They found a significant difference in the amount of lumbar lordosis in patients with a higher degree of degenerative disc changes compared to lower degree degenerative changes. While they did not determine a threshold value, they concluded that leaving a pre-operatively present hypokyphosis or a thoracic kyphosis of less than 18° represents an unfavourable surgical outcome. Incongruence of the spino-pelvic junction has also been shown to affect disc hydration patterns as signs of early degenerative changes [4]. A study by Senteler et al. found that spino-pelvic incongruence results into higher shear stresses in the lumbar discs even in the absence of fusion [21], which may be aggravated further by an anterior shift of the SVA. In the present study, the number of patients with selective thoracic fusions was not big enough to stratify according to pelvic incidence and therefore account for spino-pelvic incongruence. A further influence of the spino-pelvic organisation on the sagittal profile after selective thoracic fusions for AIS correction could therefore not be established, yet the mechanical consequences of the resulting hypolordosis are well described.

Besides lumbar hypolordosis with anterior shift of the SVA, other junctional problems have also been identified in relation to post-operative thoracic hypokyphosis with potential surgical factors resulting into or not addressing the hypokyphosis [13]. In particular, posterior all screw constructs have been described to more likely result into post-operative hypokyphosis [22] with associated junctional adaptations. Indeed, in the study by Matsumoto et al. 31% patients had post-operative hypokyphosis which was not present pre-operatively [6]. Newton et al. [7] suggested to carry out Ponte-type of osteotomies in the hypokyphotic area with particularly release of the ligamentum flavum which acts as a strong restraint to posterior column lengthening. A study investigating the amount of mobility gained by doing sequential releases indicated that osteotomy of the superior articular processes may not be necessary but that release of

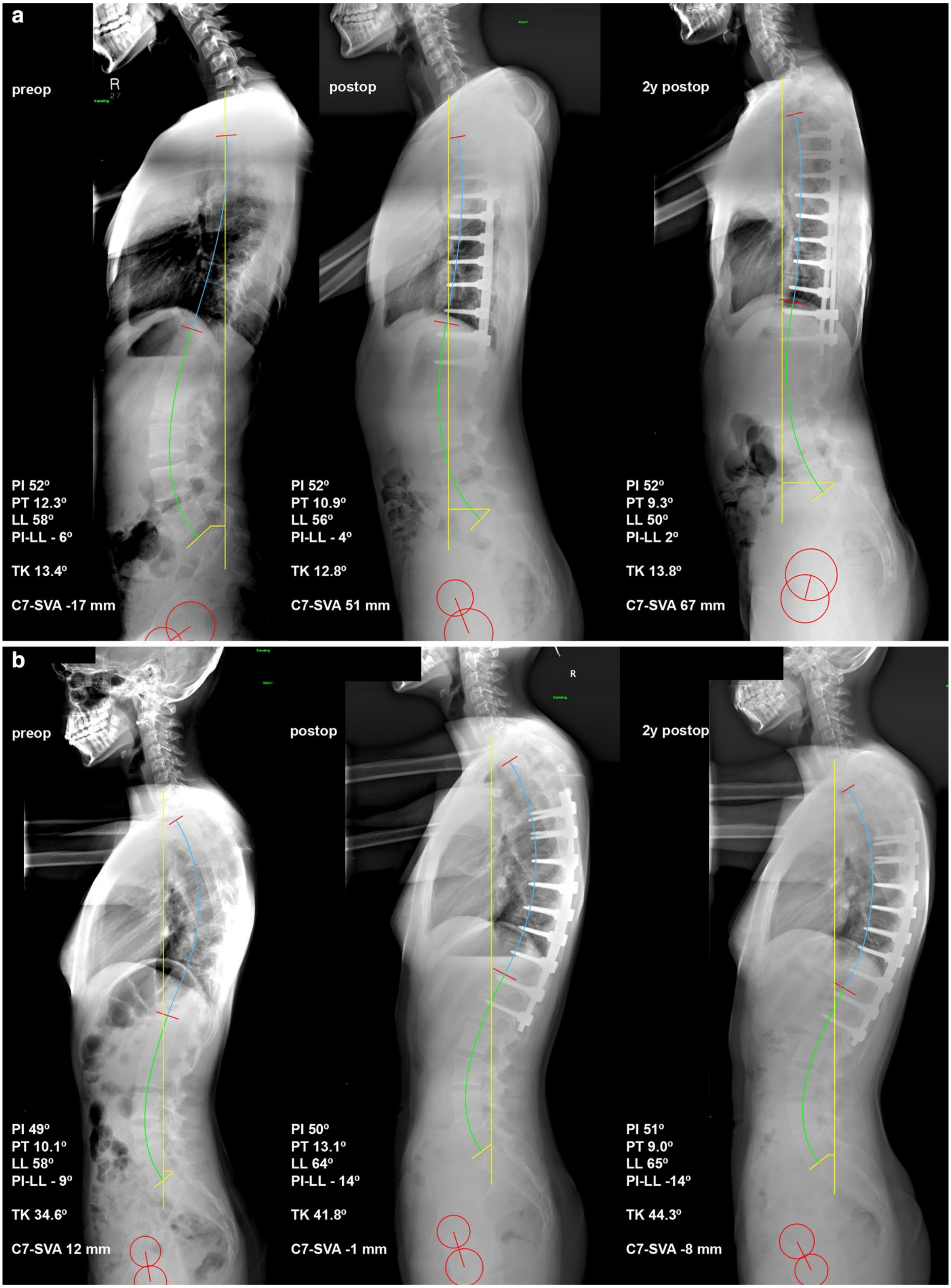


Fig. 3 Two examples of the sagittal profile of a patient in the HYPO (**a**) and CTK (**b**) groups. The patient in **a** has a thoracic kyphosis (TK) of around 13° pre- and post-operatively and in the course of 2 years shows an anterior shift of the C7 sagittal vertical axis (SVA) from pre-operatively −17 mm to +67 mm at years. In **b**, the pre-operative TK of > 30° was maintained and even slightly increased; the sagittal plane in terms of the C7 SVA was largely maintained. The images also depict how the lumbar lordosis and thoracic kyphosis were measured as the true lumbar lordosis from S1 to inflection point and the TK from thoracolumbar inflection point to last upper thoracic vertebra before the TK angle started decreasing. The C7 SVA was measured as by definition from the midpoint of the superior endplate of C7

the ligamentum flavum results into adequate mobility for posterior column lengthening and thereby kyphosing the segment [23]. Lastly, depending on the flexibility of the spine and extent of the deformity, aiming for as much coronal correction as possible may jeopardise correction in the sagittal plane which one must be aware of [24]. This could result into either maintained or new hypokyphosis of the thoracic spine, and it should be accounted for in the planning.

The main limitation of this study is the fact that all measurements were performed on a lateral whole spine plain film in 2D, particularly as this measurement has been shown to underestimate the true Cobb angle measurement in 3D [25]. However, at present 3D measurements are not carried out in routine clinical practice and a comprehensive 3D classification of scoliosis is currently still missing. While the cut-off value for a critical thoracic kyphosis may likely be different in 3D, it is not certain that this type of measurement would result into more accurate surgical planning which at present cannot be done in 3D.

The present study indicates that hypokyphosis in the sagittal plane is part of the deformity, and particularly when selective thoracic fusions are planned, the sagittal aspect of the deformity should not be neglected. A critical thoracic kyphosis of 23° and more should be aimed for in hypokyphotic patients to potentially avoid post-operative sagittal plane deterioration with mechanical and likely also clinical consequences.

Compliance with ethical standards

Conflict of interest The authors declare no conflicts of interest related to this work.

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