

Thoracic sagittal plane variations between patients with thoracic adolescent idiopathic scoliosis and healthy adolescents

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Abstract

Purpose To analyze the sagittal thoracic parameters of different types of progressive thoracic adolescent idiopathic scoliosis (AIS) patients and compare them with healthy adolescents.

Methods 115 AIS patients with main thoracic curves (Cobb: 59.4 ± 12.7) were prospectively compared with 116 healthy adolescents. The AIS and control (C) groups were homogeneous in terms of age and gender. Standing sagittal radiographs were analyzed for differences in T5–T12 kyphosis, T5–T8 and T9–T12 segmental kyphosis, the change between these two angles, and the double rib contour sign. Statistical analyses were performed using the χ^2 , one-way ANOVA, Mann–Whitney *U* and Student's *t* tests.

Results The sagittal parameters of Lenke 1 curves did not differ from healthy adolescents (T5–T8: 17.1 ± 10 vs C: 16 ± 7 ; T9–T12: 6.3 ± 7 vs C: 7.9 ± 5 ; T5–T12: 23.9 ± 14 vs C: 23.9 ± 8). Compared with the controls, Lenke type 3 curves were globally more hypokyphotic (T5–T12: 18.9 ± 12 vs C: 23.9 ± 8 , $P = 0.027$) due to a “lordosis” of the lower thoracic segment (T9–T12: 0.9 ± 10 vs C: 7.9 ± 5 , $P = 0.001$). Type 2 curves tended to exhibit more pronounced upper thoracic kyphosis (T5–T8: 20.7 ± 12 vs C: 16 ± 7). Both types 2 and 3 require a marked TK changes in the transition between the upper and lower thoracic segments to compensate for global (T5–T12) kyphosis.

Conclusions In this 2D analysis of moderate AIS, Lenke 1 curves exhibited normal thoracic sagittal parameters, which brings into question the effect of lordosis on the development of single thoracic curves. Lenke 3 curves exhibited lower thoracic segmental hypokyphosis, and the type 2 showed upper segmental hyperkyphosis. These results should be considered when planning a surgical strategy.

Keywords Adolescent idiopathic scoliosis · Sagittal plane · Thoracic kyphosis · Thoracic hypokyphosis · Healthy adolescents

Introduction

Historically, we have considered that the thoracic kyphosis is smaller for thoracic adolescent idiopathic scoliosis (AIS) curves when compared with those of asymptomatic controls [1–6]. Idiopathic thoracic curves are believed to be induced by this thoracic hypokyphosis [7–9]. The apical vertebral bodies are wedged shaped, with an increased anterior vertebral height, which results in a longer anterior column and a shorter posterior column [1, 10]. This anterior spinal overgrowth is thought to be due to disproportionate endochondral and intramembranous bone formation [11]. With the further flexion of a pre-existing coronal plane asymmetry, this lordosis creates a spinning moment that causes the spine to rotate and create three-dimensional scoliosis [1]. Recently, 3D image reconstructions have confirmed the presence of this local hypokyphosis [12] in thoracic scoliosis, reaffirming this theory and enhancing the importance of restoring the appropriate kyphosis when correcting these curves [4, 13].

However, these concepts are still opened to debate. Some authors have found no significant difference in

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thoracic kyphosis between patients with scoliosis and controls [14–16]. Based on the 3D reconstruction analyses, it has been reported that thoracic curves are not always hypokyphotic [17]. Indeed, half of Lenke 1 (main thoracic deformity) curves have been found to be normokyphotic when the global kyphosis is considered [18, 19]. Furthermore, local apical hypokyphosis has recently been considered to be more strongly related to curve progression than an initiating factor in the pathogenesis of idiopathic scoliosis [3, 15, 20].

Thoracic kyphosis in normal children is considerably reduced in early adolescence and reaches a minimum at approximately age 12 [9, 21, 22]. Consequently following this principle, all children of this age, whether asymptomatic or not, should have a straighter thoracic spine. Thus, our hypothesis is that the sagittal thoracic planes of patients with moderate thoracic idiopathic curves in the adolescent period are straight but similar to those of healthy patients of the same age.

The purpose of the current study was to analyze in 2D the sagittal parameters of different types of progressive thoracic AIS and compare them with the same parameters in healthy adolescents.

Materials and methods

We retrospectively registered the preoperative data of a consecutive series of patients with AIS and main thoracic deformity (Lenke type 1–4) who were scheduled for surgery at a single institution. Non-idiopathic deformities and main lumbar curves were excluded. Next, a prospective consecutive cohort of healthy adolescents who were being examined with standing AP and lateral thoracic radiographs due to respiratory benign concerns (asthma, bronchitis, etc.) were registered and used as controls (C group). The cohorts were found homogeneous in terms of age and gender.

Radiographic analyses were performed on digitalized coronal and lateral radiographs of the spines taken with patients in standing positions to determine the different measures. In the coronal plane, the coronal Cobb angle and the Lenke curve type (for the AIS group) were recorded. Two experienced attending spine surgeons measured all the radiographic data.

The standing sagittal radiographs of both groups were analyzed to identify differences in the following measures: T5–T12 kyphosis (measured from the upper endplate of T5 to the lower endplate of T12); T5–T8 segmental kyphosis (measured from the upper endplate of T5 to the lower endplate of T8); T9–T12 segmental kyphosis (measured from the upper endplate of T9 to the lower endplate of T12); and the change between these two angles (TK

Change), which was calculated by the subtraction of the two former angles. As reported in the literature, thoracic kyphosis in AIS is divided in a caudal hypokyphosis and a cranial hyperkyphosis and the turning point between these two zones corresponded to the plane of maximal rotation, which has been determined in T9. Following these reports, thoracic segmental kyphosis was measured with a cut-off at T9 [19, 23].

Rib cage deformity was also assessed by measuring the rib index or the double rib contour sign (DRCS) at the apex of the thoracic curve. The rib index was defined as the ratio of the distance of the posterior margin of the vertebral body to the most extended point of the most projecting rib contour, divided by the distance between the posterior margin of the same vertebral body and the most protruding point of the least projecting rib contour as described by Grivas [24]. In healthy adolescents, this index was always measured at T9 because this location was found to be the prevalent level at which the thoracic coronal apex was located in the AIS group, and therefore the most rotated.

The statistical analysis was performed with SPSS software (version 20, SAS Institute Inc., Cary, NC, USA). The distributions of the variables are given as the means and standard deviations. For the quantitative analyses, the Mann–Whitney *U* test was used for non-parametric variables, and Student's *t* test was used for parametric variables. The qualitative data were compared with the χ^2 test. The sagittal alignments for all curve types and healthy adolescents were compared using analysis of variance (ANOVA) to determine the statistical significance. The level of significance was set at 0.05.

Results

Two hundred and thirty-one patients were included in the study. One hundred and fifteen AIS patients with main thoracic curves (coronal Cobb angle: $59.4^\circ \pm 12.7$) were compared with 116 healthy adolescents (coronal Cobb angle: $1.7^\circ \pm 3.8$). The mean ages (AIS: 14.9 ± 1.9 years vs. C: 14.8 ± 0.9 years) and gender distributions (AIS female: 80 % vs. C female: 70 %) were homogeneous ($P > 0.05$) between the groups. All patients were white caucasians (Table 1). No Lenke type 4 curves were encountered; thus, Lenke types 1, 2 and 3 curves were further analyzed and compared with controls. The rib index was found to be significantly different between the AIS patients (2.7 ± 1.3) and controls (1.4 ± 0.3 ; $P = 0.000$).

In general, the thoracic AIS curves exhibited global T5–T12 thoracic kyphosis that was similar to that of the controls. The AIS patients were more hypokyphotic than the healthy adolescents in the lower thoracic segment (T9–T12: $4.9^\circ \pm 8.2$ vs. $7.9^\circ \pm 5.1$, $P = 0.000$) and exhibited

Table 1 Patient demographics

	AIS group	Normal adolescents (control group)	<i>P</i>
Patients (<i>n</i>)	115	116	
Age (year)	14.9 ± 1.9	14.8 ± 0.9	0.456
Gender	Male 22/female 93	Male 35/female 81	0.052
Primary Cobb angle (°)	59.4° ± 11 ± 12.7	1.7° ± 3.8	0.000*
Rib index	2.7 ± 1.3	1.4 ± 0.3	0.000*

Values are mean ± SD

a greater TK change (12.8° ± 12.7 vs. 8.7° ± 8.4, *P* = 0.001), which ultimately resulted in the same global kyphosis, T5–T12 of 23° (Table 2).

The sagittal parameters (T5–T12, T5–T8, T9–T12, and TK Change) of the Lenke type 1 curves did not differ significantly from those of the healthy adolescents (Table 3).

The type 2 curves tended to be slightly more hyperkyphotic than the other curves (TK T5–T12: 26.6° ± 13.3) and exhibited more kyphotic upper thoracic segments (T5–T8: 20.7° ± 12.1 vs. 16° ± 7) than those of the control group; however, these differences did not reach significance (*P* > 0.05). Because the Lenke type 2 patients were slightly more hypokyphotic in the lower thoracic segment than the control group (T9–T12: 5.6° ± 4.3 vs. 7.9° ± 5.1; *P* = 0.028), they required a greater TK change (15.1° ± 12.5 vs. 8.7° ± 8.4; *P* = 0.019) to finally achieve global thoracic balance (Table 4).

Compared with the controls, the Lenke type 3 curves were globally more hypokyphotic (T5–T12: 18.9° ± 12 vs. C: 23.9° ± 8, *P* = 0.027) due to a “lordosis” of the lower thoracic segment (T9–T12: 0.9° ± 10 vs C: 7.9° ± 5, *P* = 0.001). This lower segment hypokyphosis required a marked TK change in the transition between the upper and lower thoracic segments (16.1° ± 15.5 vs. 8.7° ± 8, *P* = 0.013) to compensate for the global (T5–T12) kyphosis (Tables 5, 6).

Table 2 Sagittal thoracic parameters comparing the general AIS group and Healthy adolescents

	AIS	Healthy	<i>P</i>
Thoracic Cobb(°)	59.4 ± 12.7	1.7 ± 3.8	0.000*
TK T5–T12(°)	23.2 ± 13.8	23.9 ± 8	0.366
T5–T8 TK(°)	17.7 ± 10.7	16 ± 7	0.131
T9–T12 TK(°)	4.9 ± 8.2	7.9 ± 5.1	0.000*
TK change(°)	12.8 ± 12.7	8.7 ± 8.4	0.001*
Rib index	2.7 ± 1.3	1.4 ± 0.3	0.000*

* Statistical significance

Table 3 Sagittal thoracic parameters comparing Lenke type 1 AIS curves with healthy adolescents

	Lenke type 1	Healthy	<i>P</i>
Thoracic Cobb(°)	55.5 ± 11.9	1.7 ± 3.8	0.000*
TK T5–T12(°)	23.9 ± 14	23.9 ± 8	0.677
T5–T8 TK(°)	17.1 ± 10.4	16 ± 7	0.409
T9–T12 TK(°)	6.3 ± 7.8	7.9 ± 5.1	0.054
TK change(°)	10.9 ± 11.4	8.7 ± 8.4	0.066
Rib index	2.6 ± 1.3	1.4 ± 0.3	0.000*
Num patients	69	116	

* Statistical significance

Table 4 Sagittal thoracic parameters comparing Lenke type 2 AIS curves with Healthy adolescents

	Lenke type 2	Healthy	<i>P</i>
Thoracic Cobb(°)	62.7 ± 9.4	1.7 ± 3.8	0.000*
TK T5–T12(°)	26.6 ± 13.3	23.9 ± 8	0.734
T5–T8 TK(°)	20.7 ± 12.1	16 ± 7	0.185
T9–T12 TK(°)	5.6 ± 4.3	7.9 ± 5.1	0.028*
TK Change(°)	15.1 ± 12.5	8.7 ± 8.4	0.019*
Rib index	3 ± 1.5	1.4 ± 0.3	0.000*
Num patients	20	116	

* Statistical significance

Discussion

There is controversy in the literature (Table 7), as whether AIS patients present normal values of thoracic kyphosis, because reported values on normal adolescents show disparity between authors. Before and at the peak of the growth spurt, healthy children have smaller thoracic kyphosis and more posterior inclination of individual vertebrae as compared to after the peak of the growth spurt [21, 25]. So thoracic kyphosis in normal children is believed to be considerably reduced in early adolescence, reach a minimum at approximately the age of 12, and later grow and establish normal values at the end of growth [9,

Table 5 Sagittal thoracic parameters comparing Lenke type 3 AIS curves with Healthy adolescents

	Lenke type 3	Healthy	<i>P</i>
Thoracic Cobb(°)	63.9 ± 16	1.7 ± 3.8	0.000*
TK T5–T12(°)	18.9 ± 12.3	23.9 ± 8	0.027*
T5–T8 TK(°)	17 ± 10.3	16 ± 7	0.608
T9–T12 TK(°)	0.9 ± 10	7.9 ± 5.1	0.001*
TK change(°)	16.1 ± 15.5	8.7 ± 8.4	0.013*
Rib index	2.5 ± 1	1.4 ± 0.3	0.000*
Num patients	27	116	

* Statistical significance

21]. Normal thoracic kyphosis has commonly been described to range from 20° to 40° [2, 4, 26], although reference values ranging from 10° to 50° have also been suggested [27, 28], with no difference between males and females [29]. Upasani and Mac-Thiong estimate thoracic kyphosis in healthy adolescents to be 27° and 44°, respectively [3, 30], and Lenke's classification only considers curves as hypokyphotic if the sagittal Cobb is less than 10° [31].

The majority of reports have found very similar values of thoracic kyphosis among thoracic AIS curves, ranging from 18° to 33°, with a pooled mean of 23.8° [16] (Table 7). Our figures (23°) are similar to those published [2–6, 32, 33]. And with these figures in hand, many authors have reported that thoracic kyphosis is smaller in thoracic AIS curves than in controls.

In contrast, some authors have found no significant differences in thoracic kyphosis between patients with scoliosis and controls [14, 15]. Based on the 3D reconstruction analyses, some authors have demonstrated that thoracic curves are not always hypokyphotic and can be divided into different groups based on the location of the plane of the maximum deformity, whether the curves are in a lordotic or kyphotic area [17, 23]. Indeed these authors have proved that half of Lenke type 1 curves are normokyphotic with an average T4–T12 kyphosis of 33°, which could explain why normokyphosis values in the range of 10° to 40° (N) are the most common sagittal thoracic

modifiers observed in AIS based on the Lenke classification (75 % of the patients), while hypokyphosis (–) represents only the 14 % [31]. Recently Ries has demonstrated with plain radiographs, that adolescents with Lenke I or II curves have comparable sagittal profiles with those of healthy controls of the same age, suggesting that Lenke I and II curves may not be hypokyphotic as previously thought [16].

Considering only the global kyphosis, we can say based on our results that thoracic AIS patients exhibit a low T5–T12 thoracic kyphosis similar to that of healthy peers of the same age. This thoracic kyphosis is straight, with values falling in the lower range of normality. Thus, the theory that a straighter spine is present during the growth spurt of adolescence (in both AIS and asymptomatic patients) seems reasonable [9, 21, 22, 25].

One well-consolidated theory supports that progressive AIS is attributable to relative anterior spinal overgrowth that leads to thoracic hypokyphosis primarily in the two or three most apical segments of the spine, which is followed by increasing axial rotational instability [7, 8, 34]. Recent 3D reconstructions of thoracic scoliosis spines have reaffirmed a consistent loss of kyphosis within the five thoracic apical vertebrae [12].

However, some controversy has recently arisen. Some authors have observed that thoracic hypokyphosis is strongly related to curve progression [3, 15, 20] and to Roussouly's sagittal type 3 and 4 profiles, showing greater pelvic incidence and lumbar lordosis in patients compared with healthy controls [2, 3, 6]. Together, these findings suggest that by facilitating axial rotation, this reduced kyphosis could be viewed as being permissive to progression rather than an initiating factor, in the pathogenesis of idiopathic scoliosis [3, 15, 20].

In the current study, we have seen that thoracic AIS curves exhibited a slightly more hypokyphotic lower thoracic T9–T12 segment compared with those of controls (5° vs 8°), in addition to a marked change in the proximal T5–T8 kyphosis (12° vs 8°). Thus, even if we consider the scoliosis patients to be globally slightly more hypokyphotic, not all of the segments of the thoracic spine are more hypokyphotic. This lower segment hypokyphosis in AIS,

Table 6 Sagittal thoracic parameters differences between all Lenke type curves and healthy adolescents

Lenke type	1	2	3	Healthy	ANOVA
Thoracic Cobb(°)	55.5 ± 11.9	62.7 ± 9.4	63.9 ± 16	1.7 ± 3.8	0.000*
TK T5–T12(°)	23.9 ± 14.3	26.6 ± 13.3	18.9 ± 12.3	23.9 ± 8.2	0.075
T5–T8 TK(°)	17.1 ± 10.4	20.7 ± 12.1	17 ± 10.3	15.9 ± 6.8	0.203
T9–T12 TK(°)	6.3 ± 7.8	5.6 ± 4.3	0.9 ± 10	7.9 ± 5.1	0.000*
Change TK(°)	10.9 ± 11.4	15.1 ± 12.5	16.1 ± 15.5	8.7 ± 8.4	0.002*
Rib index	2.6 ± 1.3	3 ± 1.5	2.5 ± 1	1.4 ± 0.3	0.000*

* Statistical significance

Table 7 Summary table of literature review describing characteristics of thoracic kyphosis in adolescent idiopathic scoliosis and healthy adolescents

Authors	Study design	TK in AIS	TK in controls	Conclusion
Dickson et al. [1]	70 thoracic AIS and 11 cadavers analyzed with X-rays	TK = 20° 75 % of patients with 2–3 apical levels in lordosis of 3°. There is anterior column overgrowth	Based on Willner [21]: thoracic AIS patients had flatter TK than normal children	Coronal deformity is the product of lordosis plus rotation
Mac-Thiong [2]	Sagittal parameters evaluated on lateral X-rays of 160 AIS patients were compared to that reported in the literature for normal adolescents	T4–T12 = 23.1° ± 11.2° King I: 20.4° ± 8.4° King II: 22.0° ± 11.1° King III: 20.3° ± 12.0°	Literature report a normal TK range of 20°–40°	TK for patients with a thoracic curve was relatively small, as compared with normal accepted values of TK
Upasani et al. [3]	Multicenter database to compare X-rays between 53 thoracic AIS curves and 50 normal adolescents	Lenke IA, B T5–T12 = 18.9° ± 11.5° (17°–46°)	T5–T12 = 27.9° ± 7.9° (11°–48°)	The thoracic curve group had a significantly decreased thoracic kyphosis relative to controls
Sucato et al. [4]	Multicenter surgical database retrospective, 353 main thoracic AIS	Lenke 1, 2, 3 T5–T12 = 23.7° (19°–25°)	Literature reported normal ranges	Patients with AIS are characterized by preoperative thoracic hypokyphosis
Janssen et al. [25]	3D analysis of spinopelvic alignment in 60 asymptomatic young adult	No AIS group	T4–T12 = males 37° ± 7.3°, females 35° ± 10°	Males and females have a different sagittal spinopelvic alignment. Female spine is more dorsally inclined
Lonner et al. [5]	Multicenter AIS database of 526 patients compared to normal adolescent lateral spine radiographs	T5–T12 = 22° In the analysis only patients with TK less than 22° (25%) were included	Based on Bernhardt and Bridwell [28] who defined normal T3–T12 = (20°–50°)	Decreased kyphosis has been long recognized as a component of the 3-D deformity in AIS
Roussouly et al. [6]	132 AIS and 50 AS from a radiological database were compared to measurements in an historical control cohort of adolescents	Global AIS population TK = 27.8° ± 18.9°	Mac-Thiong et al. [30] Historical control cohort TK = 44° ± 10°	Thoracic kyphosis values were lower than average
Propst-Proctor et al. [14].	Radiographic retrospective study: 104 normal children and 114 scoliotic patients	T5–T12 = 28° (range 16.5°–36°) in scoliotic patients	T5–T12 = 27° (range 21°–33°) in normal children	No significant relationships were noted between degree of scoliosis, age, sex, height or weight, and kyphosis, or lordosis
Rigo et al. [15]	Compare the sagittal configuration of the spine in two groups of girls with (207) and without scoliosis (45) of the same age	TK = 48.7° ± 9.4°	TK = 51.5° ± 10°	Non-scoliotic girls and those with a mild scoliotic curve had the same angle of thoracic kyphosis and lumbar lordosis
Ries et al. [16]	Retrospective case-control study, 50 thoracic AIS cases compared with 32 healthy controls of the same age, as well as with previously published reports	Lenke I or II T5–T12 = 25.4° (21.6–29.2)	(a) False-positive referrals T5–T12 = 23.5° (20.4°–26.5°) (b) Literature TK = 23.8° (18°–33°)	AIS Lenke I, II have comparable sagittal profiles with those of healthy controls of the same age. May not be hypokyphotic as previously thought
Schlösser et al. [22]	156 healthy controls (false-positive referrals) between 7 and 18 years	No AIS group	T4–T12: Before growth spurt: 29° ± 8° At growth spurt 34° ± 10° After growth spurt: 39° ± 9°	Thoracic spines of healthy girls during the growth spurt are more posteriorly inclined, and thus rotationally less stable
Present study	Comparison of 115 thoracic AIS with 116 healthy adolescents	Lenke 1–3 T5–T12 = 23.2° ± 13.8° Lenke 1: 23.9° ± 14° Lenke 2: 26.6° ± 13.3° Lenke 3: 18.9° ± 12.3°	Healthy adolescents T5–T12 = 23.9 ± 8	AIS patients have a reduced TK but similar to that of healthy peers, and within the lower normal values for this age.

All values are expressed as mean ± SD

AIS adolescent idiopathic scoliosis, TK thoracic kyphosis

makes that segment more prone to rotational instability. Analyzing the different curve types, we find that different thoracic curve patterns describe different sagittal thoracic profiles.

None of the studied sagittal parameters of the Lenke type 1 curves (single thoracic curves), differed significantly from those of the healthy adolescents (Fig. 1). This finding brings into question the influence of apical lordosis on the development of single thoracic curves.

The Lenke type 2 curves (double thoracic curves) were slightly more hyperkyphotic (T5–T12 of 26°), and most of the kyphosis originated in the upper thoracic segments T5–T8 (20°), (Fig. 2). This finding can be seen during surgery, when the cranial segment of the thoracic spine falls into kyphosis, which makes it difficult to set the anchor points at the thoracic proximal levels. A way to correct this hyperkyphosis would be to use Ponte osteotomies along with convex rod compression. However, surgeons should be aware of this circumstance and develop a tendency to over-bend the rod in the upper thoracic segment to prevent proximal junctional kyphosis from excessive correction.

The most hypokyphotic curves were the Lenke type 3, double major curves, which exhibited a T5–T12 thoracic kyphosis of 19° . In the transition to the lumbar coronal curve (the change between curves), the lower thoracic segment acted in the sagittal plane as an abnormal upward continuation of the lumbar lordosis [1, 19, 23], and showed a T9–T12 kyphosis of nearly 1° (Fig. 3). To enable appropriate sagittal balance, the upper segment consequently developed hyperkyphosis and divided the thoracic kyphosis at the apical T8–T9 levels into a cranial hyperkyphosis and a caudal hypokyphosis. The most cranial

vertebra of the hypokyphotic segment in the sagittal plane corresponded to the most rotated vertebra in the transversal plane, and to the apical vertebra in the frontal plane [19, 23], which continues 4–5 levels down into the lumbar spine [1, 3, 19]. Vertebral rotation is maximal at the cranial levels of this zone, and these vertebrae are located around the sagittal and coronal apices. This issue is important when selecting the corrective maneuver to use during surgery, because rod derotation or apical screw-derotation may increase this lordosis and flatten the spine. The use of all pedicle screw constructs has a significant hypokyphotic effect on thoracic sagittal plane alignment and if post-operative thoracic kyphosis is excessively decreased, the cervical spine may decompensate into significant kyphosis [6]. In such cases, medial translational maneuvers with extended screws, bands or wires following Asher's principles of bringing the deformity into a concave rod molded with the desired kyphosis; the use of posterior Ponte osteotomies in distraction; different contouring of the concave (over contoured) and convex (under bended) rods to facilitate rotation; rigid rods; or anterior approaches can better restore thoracic kyphosis [4, 13, 35].

One limitation of our study is that lateral views were taken with standard lateral radiographic projections. The measurement of thoracic kyphosis with the Cobb method on lateral radiographs tends to underestimate the loss of thoracic kyphosis in patients with thoracic scoliotic curves due to the rotational component [10]. To perceive the true apical sagittal profile of thoracic scoliosis, the beam should be rotated by approximately 10° to eliminate the effect of vertebral rotation, or a 3D reconstruction tool should be used to obtain a "true lateral" view of the deformity [10, 12, 36].

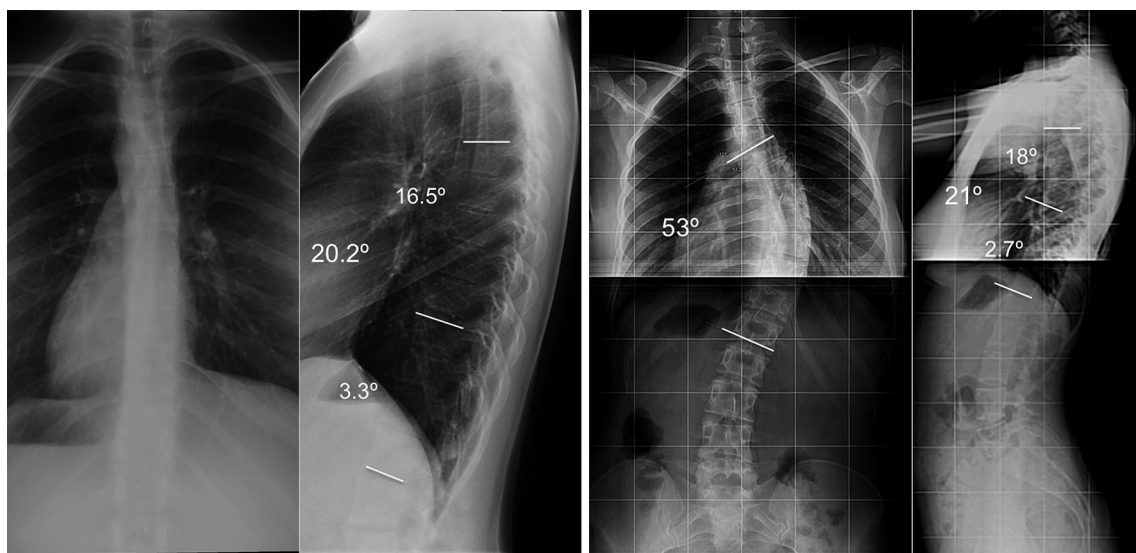


Fig. 1 Comparison between a healthy girl and a Lenke 1AN girl. Healthy patient: MT Cobb 7.8° ; T5–T12: 20.2° , T5–T8: 16.5° , T9–T12: 3.3° . Lenke 1AN patient: MT Cobb 53° , T5–T12: 21° , T5–T8: 18° , T9–T12: 2.7°

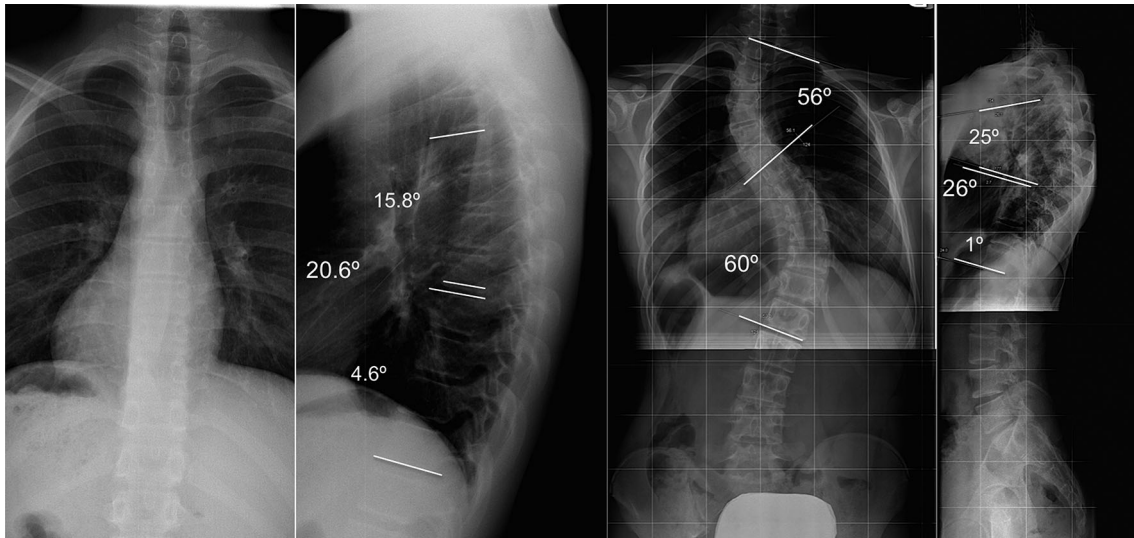


Fig. 2 Comparison between a healthy girl and a Lenke 2AN girl. Healthy patient: MT Cobb 0.9°, T5–T12: 20.6°, T5–T8: 15.8°, T9–T12: 4.6°. Lenke 2AN patient: PT Cobb: 56°, MT Cobb: 60°, T5–T12: 26°, T5–T8: 25°, T9–T12: 1°

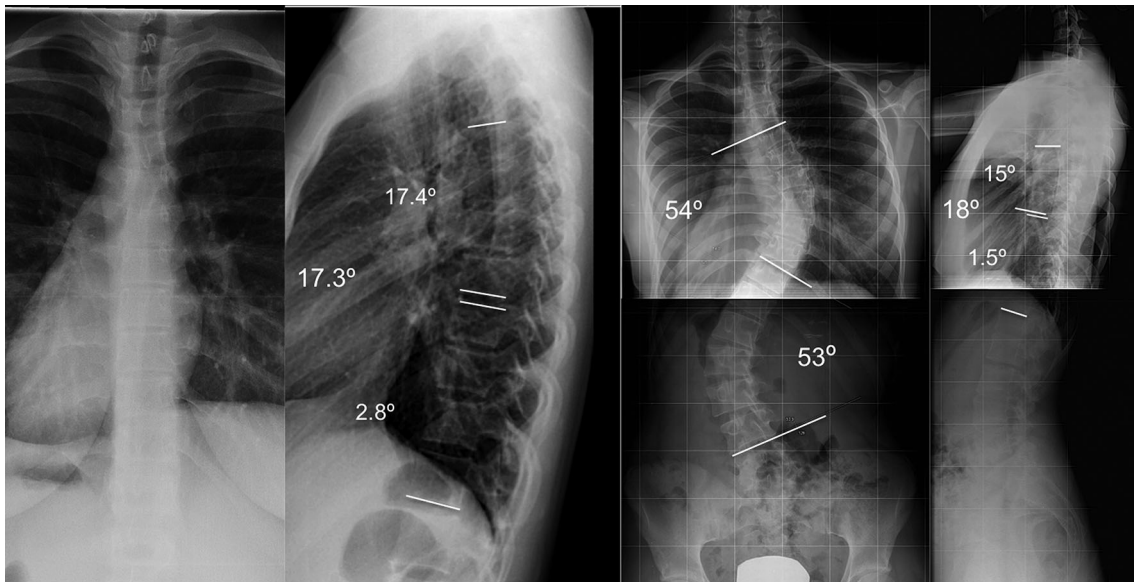


Fig. 3 Comparison between a healthy girl and a Lenke 3CN girl. Healthy patient: MT Cobb: 0°, T5–T12: 17.3°, T5–T8: 17.4°, T9–T12: 2.8°. Lenke 3CN patient MT Cobb: 54°, L Cobb: 53°, T5–T12: 18°, T5–T8: 15°, T9–T12: 1.5°

However, the Cobb technique describes the lateral appearance of the patient well [26], and currently remains the most commonly available system. Another limitation is that matching between cohorts depended only on chronological age and gender. We cannot assure a perfect matching as other demographic variables such as (BMI, height, weight, or skeletal age) were not available. And finally, only patients with surgical magnitude curves were included in the analyses; it is unknown whether these sagittal parameters have the same characteristics and similar relations to those of healthy among subjects with small curve sizes.

In conclusion, AIS patients have a reduced thoracic kyphosis but very similar to that of healthy adolescents and within the range of normality. Global T5–T12 kyphosis is then within the normal values for this age. The apex acts as the inflexion point. Below the apex, there is a hypokyphosis extending 4–5 segments down to finally end up in the lumbar lordosis. Above the apex, there is a change into hyperkyphosis to finally obtain a global normokyphosis of the global thoracic spine. This has variations depending on the Lenke type. Patients with Lenke type 1 curves exhibited normal thoracic sagittal

parameters, which bring into question the influence of lordosis on the development of single thoracic curves. Lenke type 3 curves exhibited lower thoracic segmental hypokyphosis, and type 2 curves exhibited upper segmental hyperkyphosis. These results should be considered when planning surgical strategies.

Compliance with ethical standards

Conflict of interest No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript

Ethical standards This study has IRB approval/Research Ethics Committee.

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