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ORIGINAL ARTICLE

Surgical growth guidance with non-fused anchoring segments in early-onset scoliosis

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Abstract

Purpose Surgical treatment of early-onset scoliosis (EOS) requires a balance between maintained curve correction and the capacity for spinal and thoracic growth. Spinal fusion creates irreversible conditions that prevent the implementation of further treatment methods. Our hypothesis was that non-fused anchors in growth guidance show a comparable outcome as the technique described in the literature, which involves spondylodesis of the anchoring segments.

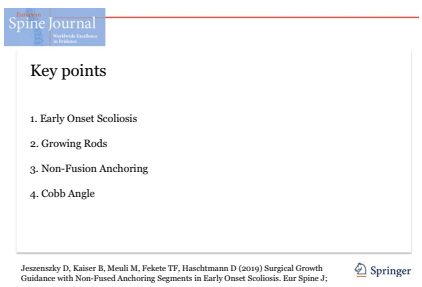
Methods This retrospective study analysed 148 surgeries in 22 EOS patients (11 female, 11 male) over a 15-year period. Patients underwent surgery with non-fused anchors and growth guidance techniques. Scoliosis, kyphosis, growth and anchoring segments were measured. For the latter, a new measuring technique was developed. Complications were recorded and classified.

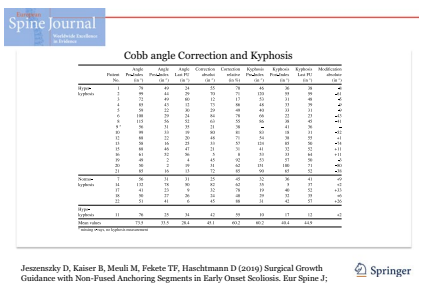
Results The mean Cobb angle reduced from 73.5 ± 24.4° to 28.4 ± 16.2° (60.2 ± 22.9%, $p < 0.001$) at the last follow-up. Spinal growth T1–S1 and T1–T12 were 41.1 ± 23.3 mm and 24.9 ± 16.6 mm ($p < 0.001$), respectively. Growth at the cranial and caudal anchoring segment was 1.5 mm/segment/year and 1.9 mm/segment/year, respectively. A total of 63 complications were documented in 20 patients, with 40 requiring unplanned revision surgery. Definitive spondylodesis was performed in three patients.

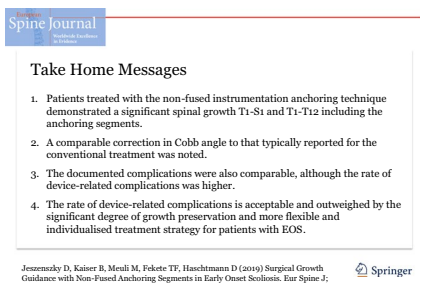
Conclusion Patients demonstrated a significant spinal growth including the anchoring segments. A comparable correction in Cobb angle and the type of complications was noted, although the rate of device-related complications was higher. No permanent impairment was reported. The rate of device-related complications is acceptable and outweighed by the significant degree of growth preservation and more flexible and individualised treatment strategy for patients with EOS.

Graphical abstract

These slides can be retrieved under Electronic Supplementary Material.







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Keywords Early-onset scoliosis · Early-onset spinal deformities · Growing rods · Growth guidance · Non-fusion anchoring

Introduction

Early-onset scoliosis (EOS), by definition, evolves before the age of five [1]. Surgical therapy for EOS requires a balance between stable curve correction and the provision for natural spinal and thoracic growth. Early infantile deformities can lead to severe cardiopulmonary complications such as pulmonary hypertension and pulmonary heart disease [2]. Early fusion in young, skeletally immature patients can result in the crankshaft phenomenon or thoracic insufficiency syndrome (TIS) and a cosmetically inferior short trunk [3].

For this reason, various growth friendly implants have been developed. According to Skaggs et al. [4], these implants can be classified into three different categories: distraction-based systems (growing rods, VEPTR [5]), compression-based systems (staples or tethers [6–8]) and guided growth systems, usually including the apex of the scoliosis (Luque trolley and Shilla [9–11]). Lately, also hybrid techniques such as unilateral magnetic distraction rods in combination with contralateral guided growth system have been introduced [12].

The fusionless approach for the treatment of scoliosis was first described by Paul Harrington in 1962 and involves a distraction rod attached to laminar hook [13]; this technique has been modified several times over the years. Akbarnia et al. [14] developed a dual growing rod technique using subfascial or subcutaneous access. Subperiosteal dissection was performed at the upper and lower anchor sites, and limited fusions with bone or synthetic grafts were carried out. Anchoring segments are defined as those to which the growth guidance system is attached with pedicle screws or lamina hooks. Lengthening of the growing rods was typically performed at 6-month intervals. From the Growing Spine Study Group database, the average patient age at the index surgery was 5.4 years, and the mean number of lengthening procedures was 6.6. A change in the baseline Cobb angle of 82° to 36° at final follow-up was described. At the time of final fusion, a total average spinal growth of 11.8 cm was measured [15].

In the case of syndrome-associated or congenital scoliosis, EOS is very complex, and both growth and curve behaviour are difficult to predict. Thus, surgical therapy must be individualised. This includes the possibility to adapt a growing rod construct in terms of its length and type without any disadvantages for spinal growth and outcome. Spinal fusions, even if only limited to the anchoring segments, result in irreversible conditions that prevent the implementation of further treatment at later stages. For example, a growing rod construct is cranially and caudally anchored around the end vertebrae with six pedicle screws. Later on, a significant curve progression with adding-on is observed, and as a consequence of this the rod has to be extended and fixed more cranially and/or distally. As a result, a significant number of segments vertebras are fused and lose their growth potential. In selected cases, if the final fusion is even shorter than the primary growing rod construct, subsequently released segments remain mobile and can contribute to spine function. A similar treatment with temporary segmental fixation is used in spine trauma or for patients with high-grade L5 spondylolisthesis [16].

The amount of loss in growth length potential as a result of premature spinal fusion can be estimated by multiplying 0.07 by the number of segments fused and by the number of years remaining for growth [17]. Hence, especially in younger children with a greater potential for growth, early fusion—even if only localised to the anchoring segments—should ideally be avoided. For this reason, we introduced into our practice a surgical procedure that involved a periosteum preserving technique and allowed growth guidance without fusion of the anchoring segments. The aim was to promote better growth and overall function. To examine the effect of the procedure, we measured spinal (T1–S1), thoracic (T1–T12) and anchoring segment growth, with a new measuring technique being developed for the latter. We expected that this advanced non-fusion technique would have a similar clinical outcome to that reported in the literature for the more conventional method of subperiosteal preparation and spondylodesis of the anchoring segments.

Patients and methods

This retrospective single-surgeon case series included 22 EOS children with a wide range of diagnoses and scoliosis aetiologies. The patients had undergone different surgical growth guidance treatment between January 2000 and July 2015. All surgeries were carried out by the first author with experience in paediatric spine surgery. The following inclusion criteria were defined: (kypho)scoliosis of any entity and diagnosed before the age of five; a minimum postoperative follow-up period of 2 years; and at least two distractions of a non-fused growth guidance system. Patients who had undergone previous spine surgeries were also included. Patient data were selected by reviewing the Misa+ ® electronic hospital charts (Corona Informatik AG, Ennetaach, Switzerland) and older printed dossiers. Complications were graded as device- or disease-related with a severity grade I to IV according to Smith et al. [18]. All radiographs were measured digitally by the same observer using the JiveX® DICOM-Viewer (PACS) (Visus Technology Transfer GmbH,

Bochum, Germany) and were independently reviewed by a second physician.

The general term "surgical growth guidance" encompasses various individualised procedures that were applied in the treatment of our patient cohort. These included different growing rod techniques (i.e. single, dual, ratchet rod, magnetic rod) linked with cross or end-to-end connectors, the Shilla™ growth guidance system (Medtronic) and segmental instrumentation. Most instrumentation devices were fixed with pedicle screws. Lamina hooks were used in seven patients. For patients with rib synostoses, rib hooks were inserted. All growth guidance systems were attached to non-fused anchoring segments.

Surgical technique

Patients were placed in a prone position on a Jackson table with specially designed Maquet-like adjustable modular foam pillows that acted as a frame. Patients under halo-gravity traction were positioned with a traction weight of 1–3 kg, depending on their body weight. In contrast to the standard subperiosteal preparation, preservation of the periosteal layer was attempted to avoid unnecessary spontaneous fusion. The correct levels were verified using fluoroscopy. The entry points of all planned pedicle screws were then identified using anatomical landmarks. Particularly with small pedicles, a 22G needle was first inserted followed by fluoroscopic verification in anteroposterior and lateral views. The pedicle was prepared with a 1.5 mm drill using a free-hand technique. Pre-bent K-wires were inserted into the holes, and fluoroscopic imaging was performed. Fine adjustment of the screw trajectories was made in a next step using a 2.0 or 2.5 mm drill for final preparation. In most cases, pedicle screws with a 3.5 mm diameter were inserted, although screws ranging in diameter from 2.7 to 5.0 mm may be used depending on the actual pedicle size. Screws are preferred to hooks or wires. Studies have shown that pedicle screws in the growing spine do not result in a clinically significant alteration in the development of the spinal canal [19–21]. Placement of the growing rods was subfascial. Distraction was carried out under intraoperative neurophysiological monitoring (IONM). Final fluoroscopic images were made to verify the correction prior to wound closure. Subsequent distractions were commonly performed between the anchoring segments at the rod connector sites. If indicated, e.g. for deformity correction at the fixation sites, for addressing screw loosening or proximal/distal extension of the instrumentation, the anchoring segments were also exposed. On this occasion, an additional distraction (or curve correction) within the anchoring segments was performed. The maintained segmental mobility could thereby be confirmed. At the beginning of the spinal growth guidance therapy, a flexible single rod with a smaller diameter (3.5 mm; Mountaineer®) was most often chosen, and during the course of the lengthening process was changed to a dual growing rod system with larger diameter rods (4.5 mm Expedium Paediatrics® or 5.5 mm Expedium normal®), if possible.

Measurement technique

All measurements were performed on conventional full spine radiographs and EOS® images (EOS Imaging, Biospace Med, version 1.77). The major scoliosis curves and kyphosis angles were measured using Cobb's technique [22]. Thoracic and spinal growth was measured in the frontal plane from the levels T1–T12 and T1–S1 (superior to inferior endplate), respectively. Growth could not be assessed for some patients because the scanned radiographs lacked any scale system. Scoliosis angles were measured prior to surgery (baseline), at the immediate postoperative time point, and at the latest follow-up examination or after final fusion. Postoperative height was determined after the index surgery as well as at the latest follow-up (Figs. 1, 2, 3, 4, 5 and 6). In addition, growth at the anchoring segments was determined in eight patients. To adapt to the new conditions during the treatment period, anchoring segments and instrumentation lengths changed in 17 patients. It was decided to perform all measures at the initial anchoring segment levels, even though the segments in the following surgeries changed in spinal level and length. All patients with osteotomies within the anchoring segments or those with additional implanted medical devices (i.e. cardiac pacemakers) overlaying the spine on the radiographs were excluded. Since a universally accepted technique to measure growth at the anchoring segments is currently lacking, the authors developed a novel measuring technique that is based on a series of lines drawn between and at right angles to the cranial and caudal anchor vertebrae (Fig. 7). Briefly, the segments are measured in the frontal plane. The first line is drawn on the superior endplate of the most cranial anchor vertebra. At 90° from the middle of the superior endplate, another line is drawn to the middle of the intervertebral disc height. The same procedure is done at the inferior endplate of the most caudal anchoring vertebra with a 90° line stemming from the middle of the endplate and connecting with the line drawn at the halfway mark (middle section) of the intervertebral disc. In the case of multiple segments, the midpoints of the intervertebral disc heights can be connected with a line. Since it was not possible to identify the middle of the endplate in all images, a well-defined point on the endplate was chosen to draw the 90° angle line. This specific point was noted for the subsequent measurements.

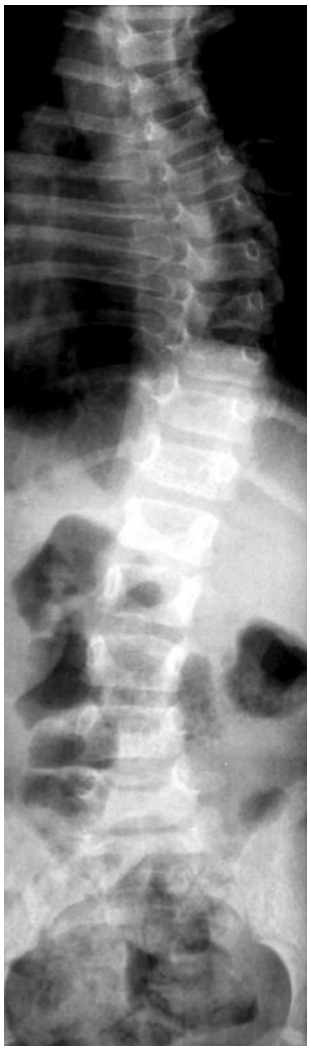

Fig. 1 Pre-index surgery Cobb angle frontal. Pre-operative frontal radiograph of the spine. Patient no. 10, 3 years old

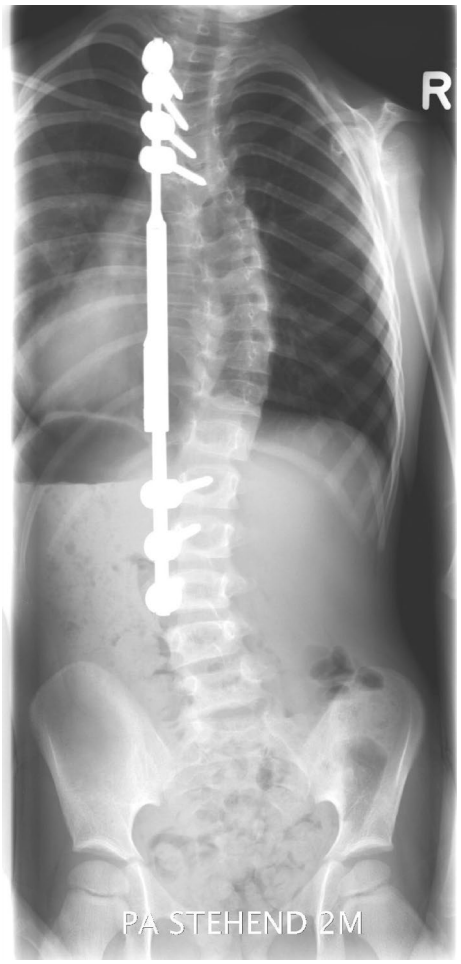

Fig. 2 Post-index surgery Cobb angle frontal. First postoperative frontal radiograph of the spine after ratchet rod implantation. Patient no. 10, 3 years old

Statistical analysis and ethics

Measurement data were managed and analysed using Excel (Microsoft® Excel 2011) and SigmaPlot (Systat Software Inc.), respectively. The differences in Cobb angle and height were examined using ANOVA. P values of < 0.05 were considered statistically significant. Local ethics approval was obtained to use the clinical data for research purposes.

Results

Patient characteristics

The baseline patient and surgery characteristics are detailed in Table 1. Of 22 patients, 11 were female and most ($n = 12$) were treated for syndrome-associated or mesenchymal scoliosis. The average patient age at the time of the index surgery was 5.0 ± 2.3 years, and the mean postoperative follow-up time was 6.9 ± 3.1 years. From a total of 148 surgeries, 144 distractions were performed. The average number of lengthening procedures was 6.5/patient (range 2–16), with the mean interval between each procedure being 1.1 ± 0.4 years (to reduce the number of surgeries and consequently anaesthesia). Twenty-five of the 144 lengthening procedures were performed at the connector or ratchet site. In 10 cases the distraction was carried out in the anchoring area and at the connector site to achieve better correction. The remaining distractions were combined with change of the instrumentation. In 41 cases the reason was device-related complications (Table 4). Other indications were spinal growth (need for a longer growing rod) and adaption to the curve characteristics. In one patient (No. 16) the distractions could be performed with a magnetic rod. Thirteen patients underwent osteotomy, 9 of them more than once during the treatment

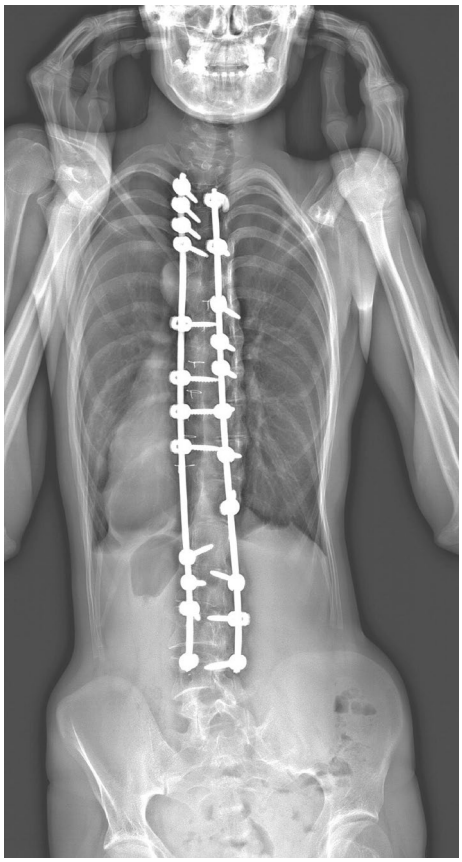

Fig. 3 Last follow-up Cobb angle frontal. Last follow-up frontal radiograph of the spine after final fusion. Patient no. 10, 14 years old

period. Six patients (nos. 5, 9, 15, 17, 21 and 22) had an open wedge osteotomy [23, 24]. In three patients (nos. 2, 13 and 20) VCR [19] and in two patients (nos. 2 and 14) rib hump resection were performed. In addition, various hemivertebra, wedge resections, Ponte osteotomies, columnotomies and osteotomies of rib synostoses took place. A 360° release with a Harms cage spondylodesis was performed for one patient (no. 20). One patient had undergone previous spine surgeries in another clinic (no. 21). Twelve patients were treated with only one growth guidance system type, whereas seven and three patients were treated with two and three different growth guidance systems, respectively, during the treatment period. Treatments were as follows: twelve patients with a single growing rod (three patients had a ratchet rod in the beginning), eight patients with dual growing rods, eight patients had non-fusion segmental pedicle screw instrumentation, one patient with Skaggs technique, one patient with Shilla™ growth guidance and one patient with a magnetic rod. Four patients had additional rib hooks and rib distraction. In 17 patients, the anchoring segment level and length changed during the treatment period.

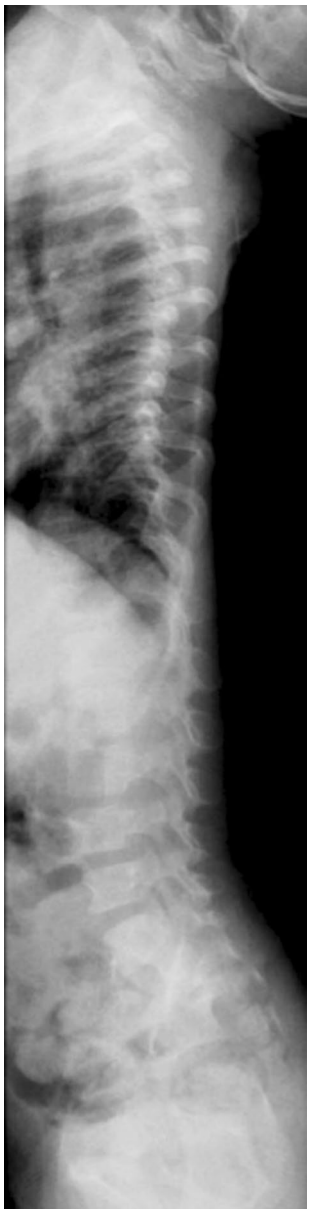

Fig. 4 Pre-index surgery Cobb angle lateral. Pre-operative lateral radiograph of the spine. Patient no. 10, 3 years old

Cobb angle correction

The mean (SD) Cobb angle of the main scoliosis curve pre-index surgery was $73.5 \pm 24.4°$ (range 41°–132°), and this was significantly ($p < 0.001$) reduced to $33.5 \pm 18.1°$ (range 2°–78°) immediately after the index surgery (Table 2). At final follow-up, the mean Cobb angle had decreased further (but not significantly; $p = 0.34$) to $28.4 \pm 16.2°$ (range 4°–60°). The mean percentage correction from pre- to post-index surgery was $60.2 \pm 22.9\%$ (range 8–92%). For five patients, the degree of correction deteriorated by more than 5° between the post-index to final follow-up time points.

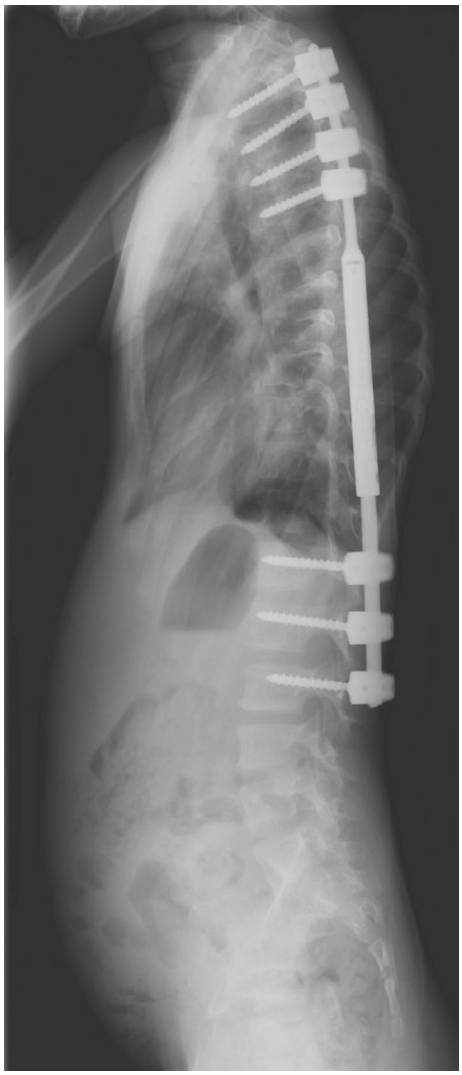

Fig. 5 Post-index surgery Cobb angle lateral. First postoperative lateral radiograph of the spine after ratchet rod implantation. Patient no. 10, 3 years old

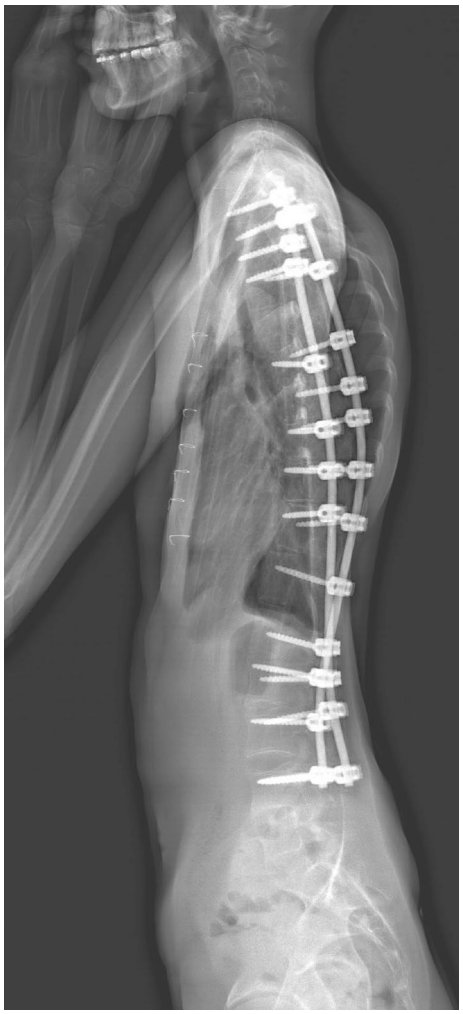

Fig. 6 Last follow-up Cobb angle lateral. Last follow-up lateral radiograph of the spine after final fusion. Patient no. 10, 14 years old

The mean pre-index surgery kyphosis angle was 60.2 ± 36.6° (range 10°–151°), and this reduced to 40.4 ± 22.1° after index surgery and remained at a similar value (44.9 ± 14°) up to the final follow-up. The majority of patients were classified as hyperkyphotic (Table 2). With the exception of three patients (nos. 12, 15 and 16), this hyperkyphosis was reduced by the time of the final assessment. Three of the normal kyphotic patients (nos. 7, 17 and 22) showed an increase to a hyperkyphotic value.

Lengthening and growth

The seventeen patients for whom lengthening and growth data were available showed a mean T1–S1 growth of 41.1 ± 23.3 mm (range 0–91 mm) and a mean T1–T12 growth of 24.9 ± 16.5 mm (range 0–58 mm) (Table 3). The average growth of T1–S1 between the post-index surgery and last follow-up was 8.2 ± 5.9 mm/year (range 0–17.8 mm/year). The patients who underwent an osteotomy procedure showed on average also a significant degree of growth ($p < 0.001$) (Table 3).

Anchoring segment lengths were unable to be measured in nine patients because osteotomies in the anchoring segments were performed after the index surgery (Table 3). For the remaining 8 patients, there was a significant mean growth in both cranial and caudal anchoring segments of 1.5 mm/segment/year (range 0.14–4.6 mm) ($p \leq 0.002$) and 1.9 mm/segment/year (range 0.3–3.6 mm) ($p \leq 0.01$), respectively. On average, cranial anchoring included 2.1 segments and caudal anchoring 1.5 segments.

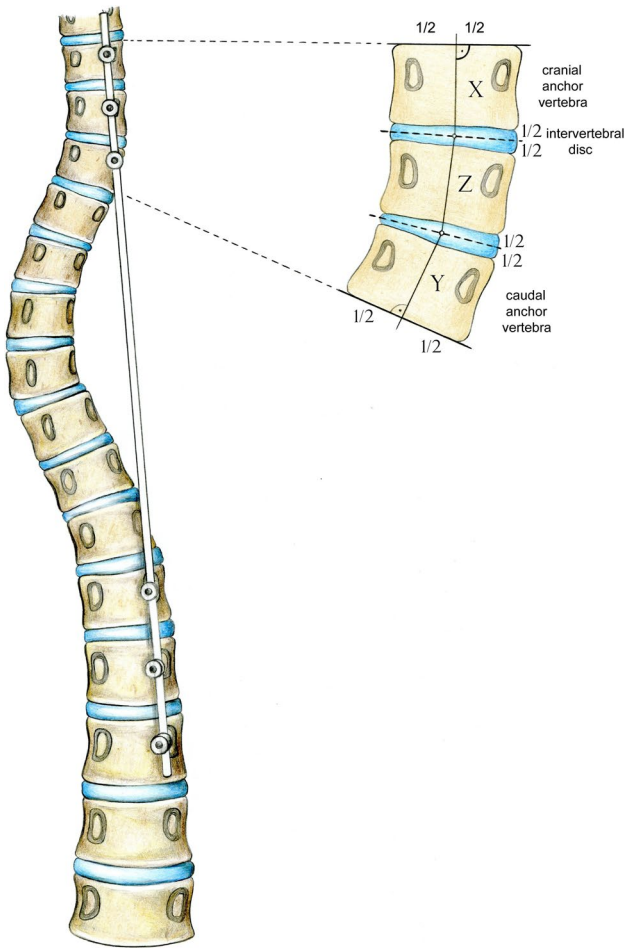

Fig. 7 Anchoring segment measuring technique. $x+y+z$ = anchoring segment height; x = connection superior endplate to the middle of the lower intervertebral disc; y = connection inferior endplate to the middle of the upper intervertebral disc; z = connection between the two intervertebral discs; for more detailed description of the measuring technique, see Sect. 2.2

Complications

Table 4 shows details of the complications. Twenty of the 22 patients had a total of 63 complications, and 40 of the latter resulted in unplanned revisions in a total of 17 patients. Twenty-three complications were treated conservatively or were resolved during the next planned growth guidance surgery. According to the classification system by Smith et al. [18], overall 61/63 complications were device-related events, mostly due to rod and screw breakage and/or loosening ($n=49$). Of note, two rod and two screw breakages occurred after documented accidents (falls). Twenty-three complications were classified as device-related events with a severity grade (SV) I and 37, SVIIA. All rod breakage complications ($n=27$) except one required revision surgery. One rod breakage was recorded during the intraoperative period. Nine screw breakages needed to be revised, whereas the remainder could be resolved during the next planned distraction surgery. One patient with a wound infection underwent two revision procedures involving flap surgery; this complication was classified as a device-related SVIIB event. Three events of IONM signal loss were recorded, but without subsequent permanent neurological deficit. Two devices malfunctioned. The ratchet rod and Shilla™ growth guidance system were not feasible because of cicatrisation. Because of a disease-related problem with the anaesthesia, the surgery for one patient had to be interrupted; this complication was classified as a disease-related SVII event. Another patient suffered from pleural effusion, which was also classified as a disease-related SVII complication. Sixteen of the unplanned revisions were completed within 6 months after the previous surgery; 24 revisions were done after the typical [25] 6-month interval between lengthening procedures. There were no cases of crankshaft phenomenon, junctional kyphosis or lordotic growth observed.

Discussion

Several growth guidance systems are currently used in the treatment of EOS, with each implant having its advantages and disadvantages. According to Skaggs et al., the implants can be classified on the basis of the forces of correction they exert on the spine [4]. Growing rods have been established as a standard technique that is based on distraction forces applied to the growing spine. Several studies describe such methods involving limited fusion of the rod anchoring segments [14, 26–31]. However, overall, the basic concept of non-fused anchors is to enable growth in as many spine segments as possible. The potential to adapt the instrumentation throughout the treatment period is potentially advantageous. For seven patients, the anchoring sites remained the same throughout the entire treatment period until final fusion, whereas for the 15 remaining patients the modified technique offered the possibility to extend or shorten the instrumentation. To the best of our knowledge, the technique with non-fused anchoring segments has never been published in the English literature. Any publications focused on fusionless scoliosis surgery still described limited fusion of the anchoring segments [32, 33]. The present study was a single-surgeon case series comprising 22 EOS patients. The mean follow-up and average number of lengthening procedures per patient are comparable to other retrospective case reviews [25, 29, 34, 35]. The interval between each lengthening procedure was 13.7 ± 4.6 months, which is considerably longer than the commonly used 6-month interval [25]. Various studies specified intervals between 6 and 10.4 months [25, 29, 33–37]. To minimise the number of surgeries, only patients with distinct curve progression and growth underwent further lengthening steps. For 37 cases of

Table 1 Patient characteristics

Patient no.	Sex	Age index surg.[c]	Follow-up (years)	Number Distr.[d]	Osteotomy	Aetiology
1	f	5.1	4.2	3	No	Central core disease
2	f	3.3	13.6[a]	8	Yes	Arthrogryposis
3	m	5.2	2.5	2	No	Myopathy
4	m	10.6	5.3[a]	7	No	Idiopathic
5	m	5.5	3.6	6	Yes	Congenital
6	m	2.9	6.2	4	Yes	Muscular dystrophy
7	m	6.0	8.3	12	No	Beals syndrome
8	f	2.6	10.7	9	Yes	Beals syndrome
9	m	5.2	8.9	7	Yes	Congenital
10	f	3.0	9.9	13	No	Marfan syndrome
11	m	4.7	7.9	4	No	SEDC[b]
12	f	5.3	9.8[a]	7	No	Prader–Willi syndrome
13	f	2.5	7.8	5	Yes	Unknown syndrome
14	m	8.3	5	4	Yes	Unknown syndrome
15	m	3.5	5.3	6	Yes	Congenital
16	f	4.3	12.2	16	Yes	Congenital
17	f	3.4	5.1	4	Yes	Congenital
18	f	10.5	3.2	4	No	Idiopathic
19	m	6.6	2.1	4	No	Beals syndrome
20	f	3.8	6.7	5	Yes	Unknown syndrome
21	f	5.4	6	5	Yes	Idiopathic
22	m	2.4	8.6	9	Yes	Congenital

[a]Final fusion

[b]Spondyloepiphyseal dysplasia congenita

[c]Index surgery

[d]Distraction

device-related complications (SVIIA), the next distraction was indicated and combined with the revision surgery.

Our patient group was heterogeneous and small, as is typical of studies on patients with EOS. Compared with similar studies, the number of congenital scoliosis patients was relatively high [27, 34, 35, 37]; this is one reason for the high number of osteotomies performed. To the best of our knowledge, no study group has focused on growth guidance in patients undergoing additional osteotomies.

Our mean pre-index surgery Cobb angle of 74° lies within the range of 61° to 92° from previously reported studies [25, 29, 33–35, 38]. The same studies concluded an overall correction rate of 51% (23–71%), which indicates that the non-fused anchoring technique achieves in a very heterogenetic patient population an above average (60.2 ± 22.9%) correction.

In the present study, the majority of patients were hyperkyphotic before the index surgery, which contrasts with previous studies [25, 33, 35, 37]. The latter studies recorded kyphoses between 22° and 59° pre-index surgery. A distinct flattening of the kyphosis was observed after the index surgery, which increased again by the final follow-up. In our study, the initial mean degree of kyphosis was relatively high with a wide range that was attributable to a patient subgroup that tended to have congenital kyphosis. These patients were partially treated with VCR. The kyphosis was reduced to an almost normal thoracic kyphotic value after the index surgery that was maintained until the final follow-up. The classification described by Lenke et al. [39] defines normal kyphosis for adolescents and was applied to our cohort because there is no well-established alternative for young children. The point remains as to whether these standard values can be translated to skeletally undeveloped immature children.

The average T1–S1 growth of 8.2 ± 6 mm/year for our patient cohort is similar to other studies that published growth rates ranging from 3 to 14.9 mm/year [25, 29, 33–35]. However, it must be considered that these studies measured growth between the pre-index surgery and the final fusion, which is usually performed after the second growth spurt. We performed a final fusion procedure in only three patients. Furthermore, not only early-onset idiopathic patients were included, but a high number of congenital and syndrome-associated EOS patients. These children often

Table 2 Cobb angle correction and kyphosis

	Patient no.	Angle pre-index (in °)	Angle post-index (in °)	Angle last FU (in °)	Correction absolute (in °)	Correction relative (in %)	Kyphosis pre-index (in °)	Kyphosis post-index (in °)	Kyphosis last FU (in °)	Modification absolute (in °)
Hyperkyphosis	1	79	49	24	55	70	46	36	38	−8
	2	99	44	29	70	71	120	55	59	−61
	3	72	49	60	12	17	53	31	48	−5
	4	85	43	12	73	86	48	33	39	−9
	5	59	22	30	29	49	40	33	31	−9
	6	108	29	24	84	78	66	22	23	−43
	8	115	56	52	63	55	86	38	45	−41
	9[a]	56	31	35	21	38	–	41	36	–
	10	99	33	19	80	81	83	18	31	−52
	12	68	22	20	48	71	54	38	55	+1
	13	58	16	25	33	57	124	85	50	−74
	15	68	46	47	21	31	41	32	52	+11
	16	61	52	56	5	8	53	33	64	+11
	19	49	2	4	45	92	53	57	50	−3
	20	50	2	19	31	62	151	100	71	−80
	21	85	16	13	72	85	90	65	52	−38
Normokyphosis	7	56	31	31	25	45	32	36	41	+9
	14	132	78	50	82	62	35	5	37	+2
	17	41	23	9	32	78	19	40	52	+33
	18	50	27	26	24	48	29	32	35	+6
	22	51	41	6	45	88	31	42	57	+26
Hypokyphosis	11	76	25	34	42	55	10	17	12	+2
Mean values		73.5	33.5	28.4	45.1	60.2	60.2	40.4	44.9	

[a]Missing X-rays, no kyphosis measurement

Table 3 Length growth

Post-index surgery	Patient no.	Tl–Sl post-index (mm)	Tl–Sl last FU[a] (mm)	Tl–Sl Gr.[b] (mm)	Tl–Sl Gr./year (mm)	T1–T12 post-index (mm)	T1–T12 last FU[a] (mm)	T1–T12 Gr. (mm)	T1–T12 Gr./year (mm)	Cr. an. seg.[c] Gr./seg. (mm)	Cr. an. seg. Gr./year (mm)	Cd. an. seg.[d] Gr./seg. (mm)	Cd. an. seg. Gr./year (mm)
No osteotomy	1	287	337	50	12	173	203	30	7	4.1	1	8.1	1.9
	3[f]	223	273	50	21	136	164	28	12	11	4.5	8.7	3.6
	4	346	391	45	9	211	252	41	8	4.2	0.83	1.5	0.3
	7	317	399	82	10	211	260	49	6	7.6	0.9	17.6	2
	15	247	252	5	1	136	140	4	1	-[e]	_[e]	4.7	0.9
	18	338	394	56	18	204	240	36	11	5.9	1.9	9.9	3.1
	19	277	314	37	18	160	189	29	14	1.9	0.92	_[e]	_[e]
Osteotomy	5	281	281	0	0	159	159	0	0	–	–	–	–
	6	252	282	30	5	161	178	17	3	–	–	–	–
	8	253	305	52	5	174	182	8	1	–	–	–	–
	9	273	364	91	10	160	218	58	7	–	–	–	–
	13	261	293	32	4	145	159	14	2	–	–	–	–
	14	306	334	28	6	180	192	12	2	–	–		–
	17	241	280	39	8	137	164	27	5	–	–	–	–
	20	177	219	42	6	90	122	32	5	–	–	–	–
	21	245	262	17	3	140	144	4	1	–	–	–	–
	22	236	278	42	5	119	154	35	4	1.2	0.1	10.6	1.2

[a]FU = Follow-up

[b]Gr. = Growth

[c]Cr. an. seg. = Cranial anchoring segment length

[d]Cd. an. seg. = Caudal anchoring segment length

[e]Only cranial or caudal anchoring segment measurable

[f]Patient 3 received growth hormone treatment

Table 4 Complications and revisions

Patient no.	Number of distractions	Complication type	Unplanned revisions
1	3	1IONM temporary loss of signal	0
2	8	1 wound infection[a]	0
3	2	–	–
4	7	2 rod, 3 screw breakages	2
5	6	Insufficient correction, 2 rod, 1 screw breakages	3
6	4	Pleural effusion, 1 rod breakage	1
7	12	6 rod breakages, 1 screw loosening	7
8	9	1 rod breakage, 2 screw loosenings	3
9	7	1 IONM temporary loss of signal, 1 screw loosening, inclined posture of the head	2
10	13	5 rod breakages, malfunction of ratchet rod	5
11	4	1 rod breakage	1
12	7	1 rod, 4 screw breakages	1
13	5	anaesthesia complication[b]	1
14	4	2 rod breakages, 2 screw pull-outs, malfunction Shilla growing rod	2
15	6	1 rod-, 1 screw breakage, 1 wound healing disorder	1
16	16	2 rod breakages, 3 screw loosenings	2
17	4	1 rod breakage	1
18	4	–	–
19	4	2 rod, 1 screw breakages	3
20	5	1 wound infection[c], screw pull-out, insufficient correction	3
21	5	Postoperative Horner syndrome	0
22	9	1 IONM temporary loss of signal, 2 screw pull-outs	2

[a]Conservative therapy

[b]Without deficits

[c]Debridement and plastic reconstruction

show inferior growth due to associated congenital organ anomalies [40]. The mean increase in T1–T12 length was also significant ($p < 0.001$). It should be borne in mind that the patients were within different growth phases during the treatment period.

Our measurements demonstrate that there was a significant growth within the cranial and caudal anchoring segments. To the best of our knowledge, no other studies have reported growth measurements of the anchoring segments. The preserved motion was also assessed repeatedly during surgeries. The wide range of values has to be regarded in view of the fact that the patient group was heterogeneous and included varying scoliosis aetiologies.

The majority of our patients experienced at least one complication that required revision surgery. However, none of the complications resulted in a permanent deficit. It should be emphasised that only 11% of all surgeries were performed within the commonly adopted 6-month distraction interval. Despite these revision surgeries, the mean interval between lengthening procedures was 1.1 ± 0.4 years. The surgery was classified as an unplanned revision if the complication was mentioned as an indication for surgery, even if the interval between surgeries was more than 6 months. This stringent definition was deliberately determined. Akbarnia et al. [25] and Wang et al. [29] addressed implant-related complications such as rod breakage, hook dislodgement, and screw pull-out during planned lengthening procedures. The types of complications recorded for our patients are common among other published study cohorts [25, 28, 29, 33–36, 41, 42]; however, we had a considerably higher number of screw loosenings. Akbarnia et al. [41] determined that motion within foundation anchors is a reason for an increased failure rate, including screw, hook and rod loosening or breakage. Therefore, one can assume that motion within the anchoring segments places greater stress on the implants in this area. When considering that the interval between surgeries was more than 1 year, the duration of stress exposure on the implants is considerably longer. Schroerlucke et al. [26] found that patients with thoracic hyperkyphosis present with a significantly higher complication rate than those with normal thoracic kyphosis. Complications such as rod breakage increased linearly with increasing kyphosis. They implied that an increased kyphosis might place greater stress (and strain) on the implants and lead to earlier rod

breakage. Sixteen patients from our group were diagnosed with hyperkyphosis. Finally, the likelihood of complications in the present study was probably increased as a result of the long-term treatment period and number of surgeries carried out. The distribution of grades of device- and disease-related complications, as defined by the new complication classification system in growing spine surgery, was similar to Smith et al. [18], although their rate for SVI and SVIIA events was 5–10% lower and for SVIIB and SVIII higher than in the present study.

Conclusion

Growth guidance with the non-fused anchoring segment technique achieves similar correction compared with values reported in the literature for the standard technique. Most hyper- and hypokyphotic patients attained a normokyphotic value after surgery. Despite the need to perform several osteotomies, our patients experienced significant spinal growth. Furthermore, we were able to document a certain level of growth within the anchoring segments. The device-related complication rate with non-fused anchoring segments of growing rods was higher compared with other studies. Most of the complications occurred later than 6 months after the previous surgery. Despite a higher complication rate, the mean interval between surgeries was still more than 1 year, which reduces the number of anaesthesia procedures throughout the treatment period and likely provides some benefit to the patient in terms of quality of life. There were no permanent deficits. The relatively high device-related complication rate is probably acceptable, especially given the significant degree of growth preservation and the individual and variable therapy options. Another benefit of this surgical method is that final fusion may be shorter than the initial instrumentation or even not always be necessary.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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