The impact of a corrective tether on a scoliosis porcine model: a detailed 3D analysis with a 20 weeks follow-up

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Received: 13 December 2011 / Revised: 25 February 2013 / Accepted: 5 March 2013 / Published online: 17 March 2013
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Abstract

Purpose Non-fusion treatment for adolescent idiopathic scoliosis generates interest due to the potential for growth preservation and mobility. Using an established porcine scoliotic model, this study aims to evaluate the global alignment and the morphology of the spine with and without application of a non-fusion corrective tether.

Methods At 12 weeks of age, 21 immature Yorkshire pigs had an induction of scoliosis. Once a 50° Cobb angle was obtained; animals were placed into one of the following groups: a scoliosis model group (SM, $n = 11$) where animals were euthanized, tether release group (TR, $n = 5$) where the inducing tether was removed, and an anterior correction group (AC, $n = 5$) where the inducing tether was removed and non-fusion corrective tether was applied. TR and AC were observed for a further 20 weeks and then euthanized. Post-mortem CT scans were used to create 3D spinal reconstructions to obtain global and morphologic parameters.

Results Maximal Cobb angle of the scoliotic deformity was significantly lower for AC ($27.9^\circ \pm 12.0^\circ$) than for the two other groups (TR $52.7^\circ \pm 10.0^\circ$, SM $48.3^\circ \pm 7.6^\circ$). AC experienced an increase in kyphosis ($24.2^\circ \pm 15.9^\circ$) compared to TR ($7.1^\circ \pm 6.4^\circ$). Correction in the axial plane was also observed in AC versus TR. Correction of vertebral wedging was found for AC compared to SM and TR in the three apical vertebrae.

Conclusions 3D realignment of scoliotic curves was observed with application of the corrective tether. The correction was the product of both mechanical action and growth modulation. These findings are encouraging for future development of a non-fusion device for the treatment of immature scoliotic curves.

Keywords Scoliosis model · Non-fusion correction · Growth modulation · Growth preservation

Introduction

Adolescent idiopathic scoliosis (AIS) is a complex three-dimensional (3D) spinal deformity. While the traditional emphasis of AIS has been on the coronal curve, AIS also exhibits sagittal, and most clinically significant, axial plane deformity [1, 2]. Decreased thoracic kyphosis has been reported to affect global sagittal alignment, while substantial axial rotation of the spine leads to rib hump deformity and thoracic shifts [3]. These deformities lead to unfavorable psychological states and can place the patient at increased risk for inadequate pulmonary ventilation [4, 5]. In the treatment of severe scoliosis, coronal curve correction remains the most common surgical objective. Current techniques are centered around the spinal fusion with instrumentation to correct the scoliotic deformity. However, spinal fusion and instrumentation results in permanent loss of spinal growth and mobility. Loss of spinal motion and imposed spinal alignment from fusion may lead to iatrogenic degenerative spine conditions sometimes requiring revision surgeries during adulthood.

Non-fusion correction of AIS has many potential advantages over current surgical strategies [6–12]. Using the natural growth of the spine to favorably realign, the scoliotic

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deformity may permit preservation of spinal growth and mobility. Favorable realignment in main thoracic curves would include all the following: induction or maintenance of thoracic kyphosis, correction of coronal wedging, and spinal de-rotation [13, 14]. The porcine spine has been found to be a good representative anatomical model for the human spine [15]. Our team has previously reported on an anterior-based non-fusion tethering technique in an established porcine scoliosis model (PSM) [16]. It was found that application of the non-fusion device resulted in progressive radiographic correction in the coronal plane (2D). The impact of the corrective device on 3D vertebral geometry and axial plane alignment has not been reported to date. The purpose of the current investigation is to evaluate the global alignment and the morphology of the spine in the PSM with and without application of a non-fusion corrective tethering technique. Our hypotheses are twofold: (1) releasing the inducing tether will lead to progression of the deformity in the coronal, sagittal, and axial plane; (2) placement of an anterior tether will correct the deformity in the three planes and induce morphometric changes in the vertebrae spanned by the tether.

Materials and methods

Study design

This was an IACUC approved study. Immature Yorkshire pigs ($n = 21$) of 11 weeks of age were obtained, and, after a 1-week acclimatization period, had surgical induction of scoliosis.

Biweekly radiographs were performed to evaluate the progression of spinal deformity. When the progressive scoliotic coronal curve reached a Cobb angle of approximately 50° (mean 9.5 weeks), animals were placed into one of the three groups (Fig. 1):

- SM: scoliosis model group ($n = 11$), animals were immediately euthanized
- TR: tether release group ($n = 5$), the inducing spinal tether was surgically removed and animals were observed for an additional 20 weeks prior to euthanization.
- AC: anterior correction group ($n = 5$), in which the inducing spinal tether was removed and an anterior corrective tether device was applied over the five apical vertebrae. Each of the five apical vertebral bodies received an experimental plate and two screws for fixation (Medtronic Sofamor Danek, Memphis, TN, USA). A synthetic flexible ligament was passed through the screw heads in a specific arrangement and locked in tension. Animals were then observed for an additional 20 weeks prior to being euthanized [16].

Fig. 1 Flowchart outlining timeline of stages in protocol of the three branches: scoliosis model group (SM), tether release group (TR) and anterior correction group (AC)

Surgical procedures and associated timelines

Scoliosis induction

The surgical procedure has been previously reported and is briefly described hereafter [17]. Scoliosis induction was achieved via a left-sided spinal tether fixated with pedicle screws and ipsilateral rib cage tethering. An immediate Cobb angle of 20° – 25° was initiated after all tethers were secured.

Tether release (TR and AC groups)

After receiving pre-anesthesia/analgesia, a 2 % lidocaine spray was used to facilitate intubation of the animals prior to isoflurane administration. Following prone positioning on a grounding pad, a shave of the dorsal thoraco-lumbar region

and sterile prep and draping was completed. A midline incision limited to the superficial surface of the upper and lower pedicle screws (T4–5 and L1–2) was made. Deep dissection of the left-sided posterior elements at the instrumented levels was pursued and pedicle screws from the primary procedure were located. Screw caps were detached from the pedicle instrumentation and the round posterior tether was removed. Wound closure proceeded in standard fashion.

Anterior correction (AC group only)

Immediately after completion of the first procedure (Tether release), animals were repositioned into the left lateral decubitus position and the right ventral-lateral thoraco-abdominal area was shaved, prepped, and draped. Oblique skin incisions overlying the apical rib of the scoliotic deformity, and the second rib below that level (~T9 and T11 rib) were made. Following sub-periosteal exposure, the two ribs were resected and the thoracic cavity opened. A double thoracotomy was performed to facilitate vertebral exposure for instrumentation placement. The apical five vertebral levels [T6–T10 or T7–T11, depending of the apical vertebra (T8 or T9)] were identified, exposed, and prepared for placement of instrumentation. Segmental vessels were cauterized, and each of the five apical vertebral bodies received an experimental plate and two screws for fixation (Medtronic Sofamor Danek, Memphis, TN, USA). A synthetic flexible ligament was passed through the screw heads in a specific arrangement (Fig. 2) and locked in tension. Wound closure proceeded in standard fashion through multilayer absorbable sutures.

Fig. 2 Correction device and placement strategy. The tethers are placed to achieve coronal correction via tension between the proximal and distal sides of the implant as well as axial rotation correction via the tension vector between the anterior and posterior sides of the implant. The implant is placed anteriorly to achieve sagittal correction

CT scan and 3D reconstruction

After the animals in each group were euthanized, the spines were extracted and fine cut, 0.6–1.0 mm interval, contiguous axial CT slices were obtained [17]. From these data, a volumetric 3D reconstruction of the spine was obtained by segmenting each slice (Amira, Visage Imaging, Richmond, Australia). Using a standardized anatomic landmark protocol [18], 121 points were applied on the reconstructed surfaces to define the morphology of each individual vertebra (21 per vertebral endplate, 17 per articular facet, 8 on the mid section of the vertebral body, 2 on the spinal process, and 2 on the spinal canal). The vertebrae involved in this study were the apex, the four vertebrae above the apex (labeled +1 to +4), and the four vertebrae below the apex (labeled –1 to –4). All the measurements described below were done on the CT scan reconstruction.

3D parameters

Reference systems

Based on the 3D reconstruction, a local coordinate system (CS) was calculated for each vertebra (Fig. 3). As suggested by the Scoliosis Research Society, these CS were defined as follows [19]: (1) Center: the middle of the two barycenters of the superior and inferior endplates. (2) Z axis: the ascending axis linking the two barycenters of

Fig. 3 Local vertebra coordinate system. (1) Center the middle of the two barycenters of the superior and inferior endplates. (2) Z axis the ascending axis linking the two barycenters of superior and inferior endplates. (3) X axis the cross product between the Z axis and the tangent axis of the posterior edge of the vertebral body, and (4) Y axis the cross product between the Z axis and the X axis

superior and inferior endplates. (3) *X* axis: the cross product between the *Z* axis and the tangent axis of the posterior edge of the vertebral body, and (4) *Y* axis: the cross product between the *Z* axis and then *X* axis.

3D evaluation of the deformity

The position and rotation of each vertebra were calculated in the local CS of the lower neutral vertebra (LNV) [19]. To characterize the shape of the deformity in a consistent manner between groups, frontal and sagittal (kyphosis) constrained Cobb angles were calculated in the LNV coordinate system between the following vertebrae: the −4 to +4 vertebra, −2 to +2 vertebra, and −1 to +1 vertebra. In addition in the frontal plane, Cobb angle was calculated between the end vertebrae of the curve.

Vertebral morphology

Using the local coordinate system for each vertebra, the following parameters were calculated to characterize the shape of the vertebral body: vertebral body height (central, anterior, posterior, concave and convex sides), and frontal vertebral wedging (in °).

Statistics

Descriptive analysis (mean, range, and standard deviations) was performed for each parameter with SPSS software (SPSS, Chicago, IL, USA). Comparisons within, and between, groups were assessed using ANOVA with Tukey post hoc tests and *t* test; a significant *p* value was set at 0.05.

Results

A total of 21 Yorkshire pigs reached endpoint-specific criteria and were retained for analysis: 11 SM, 5 TR and 5 AC. There were no differences between the TR and AC groups regarding initial induced Cobb angle (21.5° vs. 20.5°), days with deforming tether in place prior to second intervention (48.8 days vs. 42.6 days), coronal Cobb angle over the five apical vertebrae (45.5° vs. 45°) before the second

intervention, or sagittal kyphosis over the five apical vertebrae (18.5° vs. 26.5°) before the second intervention.

Impact of releasing the posterior tether (comparison between TR and SM)

Coronal Cobb angles

There was no significant difference in the maximal Cobb angle between the SM and TR groups (TR: 52.7° ± 10.0°, SM: 48.3° ± 7.6). The comparison of constrained Cobb angles revealed that the TR had a significantly smaller “−4 to +4 vertebra” Cobb angle, but a significantly larger “−1 to +1 vertebra” Cobb angle, without any significant difference in terms of “−2 to +2 vertebra” Cobb angle (Table 1; Fig. 4).

Thoracic kyphosis

No significant differences were found between groups in terms of the “−4 to +4” or “−2 to +2” constrained kyphosis. The “−1 to +1” constrained kyphosis, however, was smaller in the TR group compared to the SM group (7.1° ± 6.4° vs. 18.1° ± 10.0°, *p* < 0.005) (Fig. 5).

Axial rotation

The analysis of the axial rotation of each vertebra relative to the apical vertebra revealed that the TR group had significantly larger axial rotations than the SM group at the levels −1, +1, +2, +3, and +4 (Table 2; Fig. 6).

Vertebral morphology

The comparison of the overall vertebral height (measured at the center of the vertebral endplates and on the anterior, posterior, convex and concave walls of the vertebral bodies) demonstrated that for each vertebral level, values were significantly greater for the TR group compared to the SM group (mean difference = 0.49 cm, *p* < 0.001, Fig. 7; Table 3). The analysis of the coronal vertebral wedging within each group revealed that the SM and TR groups had significantly greater wedging of the three apical vertebrae

Table 1 Constrained Cobb angle (in degrees) in the coronal plane (LNV) between different levels (−1 to +1; −2 to +2; −4 to +4), and results of the *t* test analysis comparing the TR group to the SM group, and the AC group to the TR group

	SM		TR		AC		TR vs. SM	AC vs. TR
	Mean	SD	Mean	SD	Mean	SD	<i>p</i> value	<i>p</i> value
Cobb angle between vertebra −1 and +1	29.8	6.8	44.6	8.7	14.7	7.8	<0.001	<0.001
Cobb angle between vertebra −2 and +2	45.7	11	49.5	6.6	21	10.9	ns	<0.001
Cobb angle between vertebra −4 and +4	46.8	10.4	17.1	8.7	20.1	6.4	<0.001	ns

Fig. 4 Constrained coronal Cobb angle for the three groups between the 9 (−4; +4) apical vertebrae, the 5 (−2; +2) apical vertebrae, and the 3 (−1; +1) apical vertebrae. (SM: measurement at 9.5 weeks; for AC and TR groups: measurement at 29.5 weeks)

Fig. 5 Constrained kyphosis angle for the three groups between the 9 (−4; +4) apical vertebrae, the 5 (−2; +2) apical vertebrae, and the 3 (−1; +1) apical vertebrae. (SM: measurement at 9.5 weeks; for AC and TR groups: measurement at 29.5 weeks)

(−1, 0, and 1) when compared to levels −4, −3, +3, and +4 ($p < 0.05$). When comparing groups (Fig. 8), significant greater wedging was found for the TR groups at the level −1, 0, 3, and 4 compared to the SM group ($p < 0.05$). For the TR group, the wedging at the upper level was in the opposite direction than the apical wedging.

Impact of anterior tethering (comparison between AC and TR)

Coronal Cobb angle

Cobb angle was significantly smaller in the AC group than in the TR group (AC: $27.9^\circ \pm 12.0^\circ$, TR: $52.7^\circ \pm 10.0^\circ$; $p = 0.017$). The comparison of the constrained Cobb angles demonstrated that AC group had a significantly smaller “−1 to +1 vertebra” and “−2 to +2 vertebra” Cobb angles than

the TR group, without any significant difference in terms of “−4 to +4 vertebra” Cobb angle (Table 4; Fig. 4).

Thoracic kyphosis

No significant differences were found between groups in terms of the “−4 to +4” or “−2 to +2” constrained kyphosis. The “−1 to +1” constrained kyphosis, however, was larger in the AC group compared to the TR group ($24.2^\circ \pm 15.9^\circ$ vs. $7.1^\circ \pm 6.4^\circ$, $p < 0.05$) (Fig. 5).

Axial rotation

The analysis of the axial rotation of each vertebra relative to the apical vertebra revealed that the AC group had significantly smaller axial rotations than the TR group at the levels −1, +1, +2, +3, and +4 (Table 5; Fig. 6).

Table 2 Axial rotation (in degrees) of each vertebra relative to the apical vertebra in LNV coordinate system, and results of the *t* test analysis comparing the TR group to the SM group, and the AC group to the TR group

Vertebral level	SM		TR		AC		TR vs. SM <i>p</i> value	AC vs. TR <i>p</i> value
	Mean	SD	Mean	SD	Mean	SD		
4	13.6	8.3	28	5.2	13.3	9.8	0.001	0.008
3	9.2	5.2	21.5	4.6	8.2	9.1	0.004	0.01
2	4.7	3.1	15.2	2.9	2.2	7.6	0.001	0.003
1	1.6	3	6.9	1.8	−2.1	5.5	0.003	0.001
0	0	0	0	0	0	0	–	–
−1	0.6	2.9	1.8	2.9	−1.2	2	0.03	0.003
−2	3.2	3.1	3	3.8	2.7	3.2	NS	NS
−3	6	3.2	4.4	6.6	2.8	2.8	NS	NS
−4	12.3	5.8	9.2	5.9	7.6	5	NS	NS

Fig. 6 Axial rotation relative to the apex for the −4, −2, 2, and 4 levels in the LNV coordinate system. (SM: measurement at 9.5 weeks; for AC and TR groups: measurement at 29.5 weeks)

Vertebral morphology

The comparison between the AC and TR groups in terms of vertebral height measured at the center of the vertebral endplates (Fig. 7; Table 3) demonstrated that the vertebrae immediately adjacent to the apical vertebra were significantly smaller in the AC group than in the TR group (mean overall difference = 0.13 cm, $p < 0.05$), without any significant differences for any of the other vertebrae. Of note, the AC group has a significantly greater vertebral height than the SM group at every level (mean difference = 0.36 cm, $p < 0.001$). Further comparison of the vertebral body heights between TR and AC groups demonstrated that there were no significant differences between groups when the vertebral height was measured on the concave or posterior walls. On the other hand, the anterior and convex walls of the vertebral bodies were significantly

smaller in the AC group at the levels immediately adjacent to the apical vertebra (levels −2, −1, and +1; $p < 0.05$).

The analysis of the coronal wedging within the AC group did not reveal any significant difference between vertebral levels. The comparison of vertebral wedging between AC and TR groups revealed that the three apical vertebrae of the AC group had a significantly smaller wedging than the TR group ($p < 0.05$, Fig. 8).

Discussion

Tools for evaluating the risk of AIS progression have recently emerged based on genetic, radiographic data, and modeling [20–22]. Early identification of patients who will develop severe progressive curves can be of significant interest if early intervention options exist. However,

Fig. 7 Coronal plane vertebral body height (concave, center, and convex sides) at the all the levels between -2 to 2 for the three branches. (SM: measurement at 9.5 weeks; for AC and TR groups: measurement at 29.5 weeks)

Table 3 Vertebral body height (in cm) measured at the center of the endplates for each level (SM: measurement at 9.5 weeks; for AC and TR groups: measurement at 29.5 weeks), and results of the *t* test analysis comparing the TR group to the SM group, and the AC group to the TR group

	SM		TR		AC		TR vs. SM <i>p</i> value	AC vs. TR <i>p</i> value
	Mean	SD	Mean	SD	Mean	SD		
Vertebra +4	2.3	0.1	2.7	0.1	2.7	0.1	<0.001	0.476
Vertebra +3	2.3	0.1	2.8	0.1	2.8	0.1	<0.001	0.468
Vertebra +2	2.4	0.1	2.9	0.1	2.7	0.1	<0.001	0.024
Vertebra +1	2.4	0.1	3.0	0.2	2.7	0.1	<0.001	0.010
Apical vertebra	2.5	0.1	3.0	0.2	2.8	0.1	<0.001	0.035
Vertebra -1	2.5	0.1	3.0	0.2	2.8	0.1	<0.001	0.010
Vertebra -2	2.5	0.1	3.0	0.2	2.8	0.1	<0.001	0.016
Vertebra -3	2.6	0.2	3.1	0.2	3.0	0.1	<0.001	0.374
Vertebra -4	2.7	0.2	3.2	0.2	3.1	0.2	<0.001	0.195

currently, there are limited surgical options to treat high-risk patients. Growing rods and distraction technologies often require multiple interventions and ultimately lead to a definitive fusion. Early fusion leads to limitation in spinal and thoracic growth. Vertebral stapling techniques and partial fusions with sliding connections (Shilla) have marked limitations, as studies do not report 3D correction of the scoliotic deformity. Furthermore, these techniques are not applicable to the treatment of large deformities [23, 24]. These limitations have promoted ongoing work to establish solutions that can modulate natural growth of vertebrae without the possible need for fusion, to achieve favorable 3D alignment. The established PSM offers a

unique tool to analyze the mechanisms of non-fusion treatments on focal, regional, and global levels.

Removal of the posterior tether: a validation of the PSM

The greater size of the vertebral bodies in the TR group compared to the SM group demonstrates that inducing scoliosis does not arrest the growth of the vertebrae, although the absence of a control group without scoliosis does not allow the determination of decreased growth in SM growth potential of the vertebral bodies. The scoliotic deformity created in the PSM is associated with an axial

Fig. 8 Coronal wedging (in °) of the vertebrae for the three branches. (SM: measurement at 9.5 weeks; for AC and TR groups: measurement at 29.5 weeks)

Table 4 Posterior vertebra height in cm at all the levels between –4 and 4

Level	Posterior vertebra height (cm)						Anova <i>p</i> value between groups
	SM		TR		AC		
	Mean	SD	Mean	SD	Mean	SD	
4	2.28	0.17	2.79	0.20	2.72	0.15	<0.001
3	2.38	0.18	2.89	0.18	2.92	0.11	<0.001
2	2.43	0.18	3.03	0.18	2.79	0.21	<0.001
1	2.50	0.16	3.08	0.18	2.93	0.15	<0.001
0	2.57	0.15	3.00	0.16	2.99	0.14	<0.001
−1	2.65	0.17	3.13	0.15	3.10	0.13	<0.001
−2	2.71	0.16	3.22	0.15	3.10	0.07	<0.001
−3	2.72	0.20	3.32	0.20	3.26	0.08	0.01
−4	2.82	0.15	3.55	0.24	3.29	0.08	0.029

SM: measurement at 9.5 weeks; for AC and TR groups: measurement at 29.5 weeks

rotation resembling AIS, wherein the posterior elements of the spinal column are displaced into the concavity of the scoliotic curve.

The release of the inducing tether led to an initial decrease of the coronal spinal deformity in the PSM [16]. After 20 weeks, the Cobb angle of the TR group regained a similar level as that of the SM group. However, as illustrated by the current investigation, this deformation was not exactly the same. Current results demonstrated an increase in the Cobb angle of the apical part of the spine and a decrease in the Cobb angle at the extremities of the curve for the TR group. These results indicate that in the SM, not only was a global deformation of the spine created, but there was also a modulation of the growth for the apical vertebrae. A decrease of the kyphosis in the apical region between the SM and the TR has also been demonstrated.

This modulation is conserved after the release of the tether and increases the deformity, not only in the coronal plane, but also in the sagittal plane. This hypothesis is furthermore confirmed by a more pronounced wedging (SM and TR group) at the apical levels than at the adjacent levels. In the axial plane, the removal of the inducing tether led to a significant increase of the apical axial rotation in relation to the spine proximal to the deformity.

The detailed CT scan analysis of the global curve establishes that the PSM exhibits the typical features characteristic of thoracic AIS: coronal deformity, loss of kyphosis, axial rotation, and wedging of the vertebral bodies. It is important to highlight that the induced deformity causes growth modulation, which in turn causes further deformity as part of a vicious cycle even when the inducing tether is removed.

Effect of the anterior correction tether

The second finding of this detailed CT scan study relates to the analysis of a tether-based device for fusionless treatment of the spinal deformity.

The comparison of vertebral body heights (at the center of the endplates) between AC and SM groups demonstrated that the placement of an anterior tether does not prevent axial growth of the vertebrae. For the apical vertebrae, there is less growth at the center in the AC group than the TR group. This can be explained by a loss of growth for the instrumented vertebrae, but a recent study seems to indicate that the potential of growth is not lost rather it is redirected in the axial plane [16].

The decrease of the Cobb angle in the coronal plane for the AC group confirms that the technique applied in this study corrects the spinal deformity in the coronal plane, mainly in the apical area. The presence of a greater kyphosis for the three apical vertebra of the AC group in comparison to the TR group also indicates a correction in the sagittal plane.

The axial rotation observed in the TR group was corrected significantly in the AC group.

A comparison between the AC and the TR groups suggests that the bodies of the five apical vertebrae are impacted to grow differently. Due to the placement of the corrective tether, the anterior and the convex sides of the AC group demonstrate restricted growth in height compared to the corresponding sides of the TR group. This indicates that the growth of the vertebral body is modulated by the corrective tether and reduces the deformity of the spine. The greater wedging observed in the TR group compared to the AC group also suggests that the vertebral body modulation decreases the vertebral deformity.

The fact that there was no significant difference between the shape of the vertebrae that was not involved in the instrumentation of the anterior correction signifies that the

Table 5 Cuneiformization frontal at all the levels between −4 and 4 in the local coordinate system of each vertebra

Level	Cuneiformization frontal in the local coordinate system of each vertebra(°)						Anova <i>p</i> value (between groups)
	SM		TR		AC		
	Mean	SD	Mean	SD	Mean	SD	
4	−0.83	2.13	−7.19	7.93	−3.62	0.62	0.03
3	0.09	2.37	−8.50	6.76	0.28	2.11	0.002
2	3.40	2.41	−2.59	3.67	0.35	6.23	0.02
1	7.08	1.97	8.73	1.32	−0.57	3.77	<0.001
0	7.64	1.90	13.42	4.38	7.32	3.15	0.003
−1	8.28	2.31	13.95	3.80	6.84	2.64	0.003
−2	6.21	2.24	5.94	1.62	0.64	1.40	0.003
−3	−0.07	5.17	−2.84	3.27	3.86	5.18	0.071
−4	−6.59	5.07	−9.01	6.00	−2.77	5.92	0.289

SM: measurement at 9.5 weeks; for AC and TR groups: measurement at 29.5 weeks

observed morphologic changes concern mainly the vertebrae treated with instrumentation (−2 to 2). This confirms that the action of the corrective tether occurs mainly in the apical area. It also seems to indicate that growth modulation plays an important role in the correction of the deformation.

Comparison to human growth

While the morphology of the porcine vertebrae has been reported as being very similar to the human [25, 26], little is known regarding the similarities and discordances in terms of spinal growth. Using a control group of six normal Yorkshire pigs monitored with monthly CT scan during 9 months (unpublished data), it has been determined that the normal Yorkshire thoracic vertebra grows from 2.2 to 2.6 cm during the period corresponding to the induction of the scoliosis in the PSM animals (gain = 0.4 cm/vertebra in 6.5 weeks), and grows from 2.6 to 3.1 cm during the period corresponding to the correction of the scoliosis (gain = 0.5 cm/vertebra in 20 weeks). From the work of Dimeglio et al. [27] it is noted that a thoracic vertebra represent 2.5 % of the sitting height in an individual. A gain of 0.5 cm per vertebra (i.e., gain during the corrective phase) would, therefore, correspond to a gain of 20 cm in sitting height (reported gain between the age of 8 and 15 years for girls, and 9 to 16 years for boys). The correlation from a porcine model to AIS is not as simplistic at this simple calculation, but provides estimation. The PSM should be noted to represent a worst-case scenario given the very rigid curvature and marked degree of deformity (~50° is a common threshold for surgical fusion indication in AIS). If a tether approach (or one based on similar principles) would be transposed to correction of AIS, the timing of the surgery must take into account the remaining growth in conjunction with the structural amount of

deformity to be corrected through growth modulation. With those considerations, corrective growth modulation would be applied well before a structural curvature of 50° by maximal Cobb measure. This underlines that a tether-based approach may hold promise given effectiveness in the worst-case deformity scenario of this animal study.

Conclusions

In conclusion, the anterior correction corrects the AIS-like deformity created in the PSM, principally in the instrumented area and affecting all three planes: sagittal, coronal, and axial. The corrective process is not only a product of the mechanical action of the tether, but also the result of bone remodeling of the vertebral bodies, decreasing the wedging of the apical vertebrae. The analysis of the TR group indicates that the induced deformity can lead to ongoing growth modulation, even after the removal of the inducing tether. The growth preservation and the correction of the wedging in the AC group demonstrate that the growth modulation is a reversible process.

Conflict of interest None.

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