Does Removing the Spinal Tether in a Porcine Scoliosis Model Result in Persistent Deformity?

A Pilot Study

Ashish Patel MD, Frank Schwab MD,
Renaud Lafage BS, Virginie Lafage PhD,
Jean Pierre Farcy MD

Published online: 6 January 2011
© The Association of Bone and Joint Surgeons® 2011

Abstract

Background Using a tethering technique, a porcine model of scoliosis has been created. Ideally, tether release before placement and evaluation of corrective therapies would lead to persistent scoliosis.

Questions/purposes Does release of the spinal tether result in persistent deformity?

Methods Using a unilateral spinal tether and ipsilateral rib cage tethering, scoliosis was initiated on seven pigs. The spinal tether was released after progression to a Cobb angle of 50°. Biweekly radiographs were taken for 18 weeks after tether release to evaluate longitudinal changes in coronal and sagittal Cobb angles. Postmortem fine-cut CT scans were used to evaluate vertebral and disc wedging and axial rotation; results were compared to a previously published data set of 11 animals euthanized before release of the tether (control group).

Results Radiographic analysis demonstrated two responses to tether release: a persistent deformity group and an autocorrective group. Differences between these two

groups included number of days with the tether in place before reaching a Cobb angle of 50° and degree of deformity immediately after scoliosis induction. CT analysis of the tether release versus tether intact groups demonstrated progression in vertebral body wedging without differences in apical rotation.

Conclusions With the appropriate inducing parameters, release of the spinal tether does not systematically result in deformity correction. Tether release resulted in a reduction in Cobb angle in the first several weeks followed by steady curve progression. Deformity progression was confirmed using detailed CT morphometric analysis.

Clinical Relevance The tether release model will be used to evaluate corrective nonfusion technologies in future investigations.

Introduction

Adolescent idiopathic scoliosis (AIS) is a complex, three-dimensional (3D) spinal deformity affecting 2% to 3% of the general population [7, 24]. The risk of rapid scoliosis progression, which requires treatment, is heightened during the adolescent growth spurt [23, 25]. The mainstay of treatment for severe and/or progressive curves in the past has been spinal fusion and instrumentation.

Recently, much attention has been directed toward nonfusion technology for the treatment of AIS. Newer developments have included spinal tethering devices [4, 5, 11, 12], vertebral body staples [3], and epiphyseal systems [14]. Theoretically, an implantable internal bracing system could redirect growth to correct a scoliotic deformity. Additionally, nonfusion therapies may potentially spare spinal motion, which is advantageous compared to spinal instrumentation and fusion.

One or more of the authors (FS) has received funding from a grant from Medtronic Sofamor Danek, Inc (Minneapolis, MN). Each author certifies that his or her institution approved the animal protocol for this investigation and that all investigations were conducted in conformity with ethical principles of research.

A. Patel (✉), F. Schwab, R. Lafage, V. Lafage, J. P. Farcy
Department of Orthopedic Surgery, NYU Hospital for Joint Diseases, 380 2nd Avenue, Suite 1001, New York, NY 10010, USA
e-mail: md.ashish@gmail.com

A. Patel
Orthopaedic Department, SUNY Downstate Medical Center, Brooklyn, NY, USA

To enhance the understanding of scoliosis during growth and possibly develop animal models for applying newer scoliosis therapies, many investigators have attempted to recreate the spinal deformity of AIS [1, 4, 5, 8–10, 13, 15, 17–19]. Schwab et al. [15] recently described an experimental porcine scoliosis model (PSM). By attaching flexible tethers to the spine with pedicle screws and to the ipsilateral rib cage, progressive 3D deformities have been reliably created. CT analysis of this model demonstrated vertebral and intervertebral wedging similar to AIS. In another report [13], there was substantial vertebral rotation and rib cage dysplasia. In neither study, however, was the spinal tether released to see whether the deformities persisted.

We therefore raised the following questions: (1) Does release of the spinal tether result in persistent deformity in the PSM or do some curves autocorrect? (2) Are there differences in vertebral morphometry, ie, height, wedging, and rotation, between the tether release group and the previously described tether intact group?

Materials and Methods

We conducted a pilot investigation, using seven immature (11-week-old) male Yorkshire pigs, in this Institutional Animal Care and Use Committee-approved study. Spinal deformity was surgically initiated by unilateral spine and rib cage tethering. After animals had achieved a coronal

Cobb angle of 50°, the spinal tether was surgically removed, while the rib tether was left in place. Animals were monitored with biweekly coronal and sagittal radiographs for 18 weeks and then euthanized. Fine-cut CT scans were acquired postmortem and analyzed for vertebral morphometric data. Morphometric data were compared between the tether release group and the previously described tether intact group and followed over 11 weeks [15] (Fig. 1).

After a 1-week acclimatization period, animals ($n = 7$) underwent scoliosis induction surgery. Animals were sedated with an intramuscular combination of 30 mg/kg ketamine, 1.1 mg/kg acepromazine, and 0.04 mg/kg atropine. Two percent lidocaine spray was used to facilitate intubation, whereas 1% to 2% isoflurane was given for anesthesia. A midline incision from the T4 to L3 levels allowed exposure of the spinous processes. A left-sided paramedian muscle plane split lateral to the erector spinae complex was used to gain access to the left rib cage. After elevation of the rib periosteum, the ligamentous tethering of five ribs (T7–T11) was performed (flat polyethylene braided ligament; Cousin Biotech, Paris, France). Care was taken not to damage the intercostal bundle and/or violate the pleura. We then deepened the dissection at the superior and inferior limits of the midline incision to gain access to the spinal elements on the left. Two 4.5-mm-diameter pedicle screws of appropriate length were inserted superiorly (T4–T5) and inferiorly (L1–L2). Bicortical purchase was

Fig. 1 This flow diagram illustrates the study design.

uniformly achieved. Sublaminar cables were used to reinforce the inner two screws (T5, L2). We secured a spinal tether (Medtronic Spinal & Biologics, Memphis, TN) to the superior pedicle screws using caps. The spinal tether was passed distally intramuscularly, just superior to the rib cage. Through mild intraoperative tensioning of the spinal ligament and repositioning of the animal with coronal curvature, a mild deformity was achieved once tethers were fastened and locked to pedicle screws (Fig. 2).

Postoperatively, animals were given 1 g intravenous cefazolin for antibiotic therapy and a 3-mg fentanyl patch for pain control. Additionally, animals were given one tablet of bisacodyl for 7 days to facilitate defecation. Animals were housed at a fully US Food and Drug Administration-accredited animal housing facility with full-time husbandry staff. Animals were allowed to rest for 2 days and then encouraged to ambulate. If there were difficulties in ambulation, assisted ambulation was instituted.

Biweekly AP and lateral radiographs were acquired during the observation period of the animals to assess curve progression and instrumentation positioning. Animals were sedated with an intramuscular combination of 30 mg/kg ketamine, 1.1 mg/kg acepromazine, and 0.04 mg/kg atropine before radiographic acquisition. Curves progressed a mean ($\pm$ SD) of $21.9^\circ \pm 6.9^\circ$ (range, 12° – 33°) over the next 6.2 ± 2.4 weeks (range, 4–10 weeks) after the scoliosis induction procedure. Once a 50° curve was achieved, the spinal tether was surgically removed in a second intervention. We used 50° as the criterion for tether release because, as per our previous investigation [14], this would allow sufficient curve progression (approximately 25°) to create a bony dysplasia similar to AIS in the coronal plane.

The second procedure (tether release) was performed at a coronal Cobb angle of $50^\circ \pm 2^\circ$ (range, 48° – 52°). Instrumented vertebrae were reopened and pedicle screws

located. The previous incisions over the upper (T4–T5) and lower (L2–L3) screw caps were detached from the pedicle instrumentation and the spinal tether was removed. Wound closure was performed in a standard fashion. Tether release resulted in an immediate reduction in coronal Cobb angle of $2.7^\circ \pm 2.1^\circ$ (range, -5° – 1°). The postrelease coronal Cobb angle measured $47.3^\circ \pm 2.9^\circ$ (range, 43° – 51°) over the entire study group.

Postoperatively, animals were given 1 g intravenous cefazolin for antibiotic therapy and a 3-mg fentanyl patch for pain control. Additionally, animals were given one tablet of bisacodyl for 7 days to facilitate defecation. Animals were allowed to rest for 2 days and then encouraged to ambulate. If there were difficulties in ambulation, assisted ambulation was instituted.

Biweekly radiographs were taken for a mean 19.0 ± 2.7 weeks (range, 14–22 weeks) before animals were euthanized. Animals were euthanized with an intramuscular combination of 30 mg/kg ketamine, 1.1 mg/kg acepromazine, and 0.04 mg/kg atropine followed by 60 mg/kg intravenous pentobarbital and 80 meq intravenous potassium chloride. Spines were harvested at necropsy with a technique previously described [13] and radiographs and fine-cut CT scans obtained.

One of us (AP) analyzed all radiographs using (Surgimap®; Nemaris, New York, NY) to determine instrumentation positioning, pullout, breakage, and progressive structural spine modifications. Radiographic measurements included the maximum Cobb angle within the instrumented spine in the coronal and sagittal planes. The mean error during Cobb assessment on digital images is reportedly $\pm 2^\circ$ [6].

Fine-cut, 0.6- to 1.0-mm-interval, contiguous axial slices of the extracted spines were used to create a volumetric 3D reconstruction (Amira®; Visage Imaging, Richmond, Australia) of the deformity apex (three vertebrae and intervening two discs). One hundred twenty-one points, using a standardized specific anatomic landmark protocol [16], were applied on the reconstructed surface. These points were used to define the morphology for each vertebral and intervertebral unit (Fig. 3). Reconstruction of the distal neutral vertebra was completed to obtain a reference system to evaluate the axial rotation of the apical segments. A dedicated MATLAB® program (The MathWorks, Inc, Natick, MA) was created to obtain the following linear and angular measurements: vertebral and intervertebral angulation in the coronal and sagittal planes; vertebral and intervertebral body heights; and axial rotation versus the neutral vertebrae.

To evaluate the vertebral dysplasia quantified by CT analysis, we compared the apical segments in the tether release group ($n = 7$) with a tether intact control group ($n = 11$) [15]. Yorkshire pigs underwent identical scoliosis induction surgery as described previously; however, no

Fig. 2 A postoperative bird's eye view illustrates the left unilateral ligamentous spinal tether and ipsilateral rib cage tethering (euthanized animal with erector spinae removed). Reprinted with permission from Lippincott Williams & Wilkins from Schwab F, Patel A, Lafage V, Farcy JP. A porcine model for progressive thoracic scoliosis. *Spine (Phila Pa 1976)*. 2009;34:E397–E404.

tether release was performed. Animals were observed with biweekly coronal and sagittal radiographs until moderate to severe scoliosis was achieved (50°) and then euthanized. Radiographic and CT data of this group have been previously reported [13, 15]. Briefly, the tether intact group was observed for a mean of 10.5 weeks (range, 6–14 weeks) with a final Cobb angle of $54.7^\circ \pm 4.98^\circ$ (range, 51° – 65°) at study completion.

For all data, we calculated means, SDs, and ranges. Data were analyzed for normality using the Shapiro-Wilk test.

Fig. 3 The standardized points in this figure are placed to reconstruct vertebral end plate, spinous process, articular facets, pedicles, and spinal canal geometry.

Fig. 4 A graph shows radiographic progression in the coronal plane for the persistent deformity group and the autocorrective group. The release of the spinal tether led to a persistent deformity in five animals and a correction of the deformity in two animals.

We determined differences in coronal and sagittal Cobb angle progression after tether release using a paired Student's *t* test. We descriptively assessed differences between animals that achieved an established deformity versus animals that autocorrected. Lastly, we determined differences in vertebral and intervertebral dimensions between the tether intact and tether release groups using an unpaired Student's *t* test. SPSS[®] statistical software (SPSS Inc, Chicago, IL) was used for all statistical tests.

Results

Release of the spinal tether after deformity creation led to curve persistence in five animals (persistent deformity group) and curve correction in two animals (autocorrection group); stabilization was linked to prerelease Cobb progression (Fig. 4). The Cobb angle after scoliosis induction measured a mean of $24.8^\circ \pm 3.7^\circ$ and progressed to a mean of $49.6^\circ \pm 2.2^\circ$ in the persistent deformity group. After an initial Cobb reduction in the first 4 weeks postrelease, there was evidence of coronal curve progression in the next 10 weeks (Fig. 4). In contrast, a larger mean Cobb angle was achieved after scoliosis induction in the autocorrective group (33° and 40°). Progression to 50° took just a mean of 4.3 weeks for these two animals. There was a decrease in Cobb angle during the first 4 observation weeks postrelease, similar to the persistent deformity group. Unlike in the persistent deformity group, we observed continued reduction in the Cobb angle in the last 10 observation weeks. Both groups demonstrated mild initial lordosis after scoliosis induction (mean 5.3° for the persistent deformity group and mean 3.5° for the autocorrective group); before tether release surgery, there was a mean progression in

lordosis of $17.6^\circ \pm 12.5^\circ$ (range, 2° – 37°) in the persistent deformity group and $5.0^\circ \pm 4.2^\circ$ (range, 2° – 8°) in the autocorrective group. Tether release minimally affected the sagittal plane both immediately and at final followup for both groups.

CT analysis of all animals revealed substantial vertebral dysplasia over the deformity apex (three vertebral bodies and intervening discs). Vertebral body heights on the convex side of the deformity were always greater ($p < 0.001$) than concave vertebral body heights (Fig. 5). Additionally, there was a mean axial rotation of the apical vertebra of $17.2^\circ \pm 8.8^\circ$ (range, 4.5° – 33.1°). The tether release group demonstrated an increase ($p < 0.001$) in vertebral body height (Fig. 6) versus the tether intact

group. There was an increase ($p = 0.01$) in mean coronal vertebral body wedging in the tether release group (mean, $32.3^\circ \pm 10.2^\circ$; range, 16.0° – 47.1°) versus the tether intact group (mean, $23.0^\circ \pm 4.4^\circ$; range, 17.5° – 30.4°) (Fig. 7). There was an increase ($p < 0.001$) in the convex-concave vertebral body height difference in the tether release group versus the tether intact group (mean, 15.9 mm versus 10.7 mm). There was a decrease ($p < 0.001$) in coronal intervertebral disc wedging in the tether release group (mean, $1.9^\circ \pm 1.3^\circ$; range, 0.5° – 3.7°) versus the tether intact group versus (mean, $8.1^\circ \pm 3.7^\circ$; range, 0.7° – 13.9°). The intervertebral disc height difference (convex-concave) was less ($p = 0.01$) for the tether release group (mean, 1.7 ± 1.2 mm; range, -0.6 – 3.3 mm) than for the tether

Fig. 5A–B The graphs show total convex versus concave heights for the apical functional unit (FU): (A) three vertebral bodies (VB) and (B) two intervertebral discs (IVD). Larger ($p < 0.001$) vertebral body height and intervertebral disc height on the convexity of the deformity are seen compared to the concavity.

Fig. 6A–B Graphs show convex versus concave (A) vertebral body (VB) and (B) intervertebral disc (IVD) heights at the apical functional unit. The tether release group demonstrated an increase ($p < 0.001$) of vertebral height compared to the tether intact group on the concave and convex sides of the deformity while no differences were noted in terms of intervertebral disc height. Box = upper to lower quartile; middle band = median; bars = minimum and maximum.

Fig. 7 A graph shows the vertebral body (VB) and intervertebral disc (IVD) wedging angle in the coronal plane. The tether release group demonstrated an increase ($p < 0.01$) in vertebral body wedging and a decrease ($p < 0.001$) in intervertebral disc wedging compared with the tether intact group. T = tether. Box = upper to lower quartile; middle band = median; bars = minimum and maximum.

intact group (mean, 3.5 ± 1.4 mm; range, 1.1–6.5 mm). No differences ($p = 0.51$) were found in apical axial rotation between the tether release group ($17.2^\circ \pm 8.8^\circ$; range, 4.5° – 33.1°) and the tether intact group ($19.3^\circ \pm 3.9^\circ$; range, 14.4° – 27.1°).

Discussion

The development of effective nonfusion surgical treatments requires a proper animal model. We have created such a model with the PSM, which showed similar radiographic progression in the coronal plane as that observed in AIS [13]. Additionally, CT analysis documented vertebral and intervertebral wedging maximally in the apical region of the major curve. Axial rotation and rib hump dysplasia exhibit coupling in the PSM with similar magnitude and location as that reported in AIS [15]. To evaluate corrective treatments, it will be important to know whether release of the deforming tether results in autocorrection of the induced deformity. Specifically, this study aimed to answer the following questions: (1) Does releasing the spinal tether in the PSM result in curves that persist or curves that autocorrect? (2) Are there differences in vertebral morphometry, ie, height, wedging, and rotation, between the tether release group and the previously described tether intact group?

Our study has a number of limitations. First, because of the small sample size, statistical comparison between the persistent deformity and autocorrection groups was not

possible. Differences between groups are purely observational although, owing to the large differences between subgroups, we presume these differences would be maintained when using a larger sample size. Second, in ideal circumstances, CT scan data would be acquired at multiple time points on each “intact” animal before and after tether release to analyze vertebral dysplasia. Unfortunately, this was not possible at our institution; thus, tether release data were compared with data acquired on the tether intact animals (previous investigation). The tether intact (control group) animals underwent identical scoliosis induction and were euthanized once they reached a coronal curvature of 50° , thus representing the time point immediately before tether release in this study. Therefore, modifications in vertebral and intervertebral anatomy between the tether intact and tether release groups can be assumed to have taken place during the time after tether release. Because of the structural nature of the induced deformity, spine extraction minimally affected the integrity of the induced deformity [14]. Lastly, release of the rib tether was not attempted in this study. Rib tethering results in variable periosteal reaction and circumferential bone formation around the rib tether at 6 weeks postscoliosis induction. Releasing the rib tether would have required extensive dissection and a potential loss in standardization. We suspect the rib tether results in a greater rate of scoliosis progression and may be a potential mechanism for curve stabilization in the tether release model. Nevertheless, as a control for future corrective approaches, the tether release model (with an intact rib tether) would provide a more clinically similar AIS model.

Our observations suggest deformity persistence may be achieved even after release of the spinal tether. Deformity stabilization was influenced by the magnitude of the Cobb angle induced immediately after application of the deforming tether and the rapidity with which a Cobb angle of 50° was reached. In two animals, the induced curves autocorrected. Because of the larger Cobb angle immediately induced in these two animals, it took less time to reach a Cobb angle of 50° . The reduction in tether time in the autocorrective group resulted in less vertebral dysplasia than that experienced by the persistent deformity group. The mechanical modulation of vertebral body growth through asymmetric loading in the tethered spine is governed by the Hueter-Volkman principle [2] (growth is retarded by increased mechanical compression and accelerated by reduced loading). Our observations are consistent with the “vicious cycle” theory proposed by Stokes et al. [20–22]. We suspect the necessary initial bony dysplasia needed to obtain a mechanically “self-progressive” curve was not obtained in the autocorrective group. In other words, with a greater initial induced Cobb angle, less progression was necessary to reach a Cobb angle of 50° ,

and this progression took less time. As a result, the vertebrae in the autocorrective group did not develop sufficient dysplasia for the deformity to persist after tether release.

CT scan analysis revealed altered vertebral morphometry in the tether release group. The vertebral body heights on the convex side of the curve were larger than the vertebral body heights on the concave side of the curve in all specimens. When asymmetric mechanical loading was removed with release of the spinal tether, vertebral growth continued although at a slightly altered rate on the curve concavity as evidenced by the increase in coronal wedging between the tether release and tether intact groups. Continued progression of vertebral asymmetry after tether release again is consistent with the vicious cycle theory [21]. The induced vertebral asymmetry sets the stage for an altered mechanical environment leading to continued growth modulation. Further study is required to understand whether a threshold value for the length of time the deforming tether is in place for the deformity to persist after release of the deforming force.

Progressive AIS-like scoliosis has no parallel in animal models. Our observations in this PSM demonstrate radiographic persistence of the initially progressive deformity even after release of the inducing spinal tether. Persistence of deformity was linked to the length of time required for the Cobb angle to progress before tether release. In addition, CT morphometric analysis demonstrates progression of vertebral body wedging and ongoing vertebral growth after removal of the deforming tether. These data confirm a growth model for studying nonfusion approaches.

Acknowledgments We thank Anthony Siconolfi and Amanda Vega for their help with animal care and management.

References

- Agadir M, Sevastik B, Sevastik JA, Persson A, Isberg B. Induction of scoliosis in the growing rabbit by unilateral rib-growth stimulation. *Spine (Phila Pa 1976)*. 1988;13:1065–1069.
- Arkin AM, Katz JF. The effects of pressure on epiphyseal growth. The mechanism of plasticity of growing bone. *J Bone Joint Surg Am*. 1956;38:1056–1076.
- Betz RR, Kim J, D'Andrea LP, Mulcahey MJ, Balsara RK, Clements DH. An innovative technique of vertebral body stapling for the treatment of patients with adolescent idiopathic scoliosis: a feasibility, safety, and utility study. *Spine (Phila Pa 1976)*. 2003;28:S255–S265.
- Braun JT, Ogilvie JW, Akyuz E, Brodke DS, Bachus KN. Creation of an experimental idiopathic-type scoliosis in an immature goat model using a flexible posterior asymmetric tether. *Spine (Phila Pa 1976)*. 2006;31:1410–1414.
- Braun JT, Ogilvie JW, Akyuz E, Brodke DS, Bachus KN, Steffen RM. Experimental scoliosis in an immature goat model: a method that creates idiopathic-type deformity with minimal violation of the spinal elements along the curve. *Spine (Phila Pa 1976)*. 2003;28:2198–2203.
- Champaign S, Benchikh K, Nogier A, Mazel C, Guise JD, Skalli W. Validation of new clinical quantitative analysis software applicable in spine orthopaedic studies. *Eur Spine J*. 2006;15:982–991.
- Dubousset J. Idiopathic scoliosis: definition—pathology—classification—etiology [in French]. *Bull Acad Natl Med*. 1999;183:699–704.
- Dubousset J, Machida M. Possible role of the pineal gland in the pathogenesis of idiopathic scoliosis: experimental and clinical studies [in French]. *Bull Acad Natl Med*. 2001;185:593–602; discussion 602–604.
- Machida M, Dubousset J, Imamura Y, Iwaya T, Yamada T, Kimura J. Role of melatonin deficiency in the development of scoliosis in pinealectomised chickens. *J Bone Joint Surg Br*. 1995;77:134–138.
- Machida M, Murai I, Miyashita Y, Dubousset J, Yamada T, Kimura J. Pathogenesis of idiopathic scoliosis: experimental study in rats. *Spine (Phila Pa 1976)*. 1999;24:1985–1989.
- Mente PL, Aronsson DD, Stokes IA, Iatridis JC. Mechanical modulation of growth for the correction of vertebral wedge deformities. *J Orthop Res*. 1999;17:518–524.
- Newton PO, Farnsworth CL, Faro FD, Mahar AT, Odell TR, Mohamad F, Breisch E, Fricka K, Upasani VV, Amiel D. Spinal growth modulation with an anterolateral flexible tether in an immature bovine model: disc health and motion preservation. *Spine (Phila Pa 1976)*. 2008;33:724–733.
- Patel A, Schwab F, Lafage V, Patel A, Obeidat MM, Farcy JP. Computed tomographic validation of the porcine model for thoracic scoliosis. *Spine (Phila Pa 1976)*. 2010;35:18–25.
- Schmid EC, Aubin CE, Moreau A, Sarwark J, Parent S. A novel fusionless vertebral physeal device inducing spinal growth modulation for the correction of spinal deformities. *Eur Spine J*. 2008;17:1329–1335.
- Schwab F, Patel A, Lafage V, Farcy JP. A porcine model for progressive thoracic scoliosis. *Spine (Phila Pa 1976)*. 2009;34:E397–E404.
- Semaan I, Skalli W, Veron S, Templier A, Lassau JP, Lavaste F. Quantitative 3D anatomy of the lumbar spine [in French]. *Rev Chir Orthop Reparatrice Appar Mot*. 2001;87:340–353.
- Sevastik J, Agadir M, Sevastik B. Effects of rib elongation on the spine. I. Distortion of the vertebral alignment in the rabbit. *Spine (Phila Pa 1976)*. 1990;15:822–825.
- Sevastik J, Agadir M, Sevastik B. Effects of rib elongation on the spine. II. Correction of scoliosis in the rabbit. *Spine (Phila Pa 1976)*. 1990;15:826–829.
- Smith RM, Dickson RA. Experimental structural scoliosis. *J Bone Joint Surg Br*. 1987;69:576–581.
- Stokes IA. Analysis and simulation of progressive adolescent scoliosis by biomechanical growth modulation. *Eur Spine J*. 2007;16:1621–1628.
- Stokes IA, Burwell RG, Dangerfield PH, IBSE. Biomechanical spinal growth modulation and progressive adolescent scoliosis—a test of the ‘vicious cycle’ pathogenetic hypothesis: summary of an electronic focus group debate of the IBSE. *Scoliosis*. 2006;1:16.
- Stokes IA, Spence H, Aronsson DD, Kilmer N. Mechanical modulation of vertebral body growth: implications for scoliosis progression. *Spine (Phila Pa 1976)*. 1996;21:1162–1167.
- Weinstein SL. Natural history. *Spine (Phila Pa 1976)*. 1999;24:2592–2600.
- Weinstein SL, Dolan LA, Cheng JC, Danielsson A, Morcuende JA. Adolescent idiopathic scoliosis. *Lancet*. 2008;371:1527–1537.
- Weinstein SL, Ponseti IV. Curve progression in idiopathic scoliosis. *J Bone Joint Surg Am*. 1983;65:447–455.