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REVIEW ARTICLE

Vertebral body tethering for adolescent idiopathic scoliosis: a review

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Abstract

Purpose Adolescent Idiopathic Scoliosis (AIS) remains the most common type of pediatric scoliosis, mostly affecting children between ages 10 and 18. Vertebral body tethering (VBT) offers a non-fusion alternative to the gold standard spinal fusion that permits flexibility and some growth within instrumented segments. This article will serve as a comprehensive literature review of the current state-of-the-art of VBT in relation to radiographic and clinical outcomes, complications, and the learning curve associated with the procedure.

Methods A systematic literature review was conducted on PubMed, Scopus, and Web of Science from April 2002 to December 2022. Studies were included if they discussed VBT and consisted of clinical studies in which a minimum 2-years follow-up was reported, and series that included anesthetic considerations, learning curve, and early operative morbidity.

Results Forty-nine studies spanning the period from April 2002 to December 2022 were reviewed.

Conclusion This article illustrates the potential benefits and challenges of the surgical treatment of AIS with VBT and can serve as a basis for the further study and refinement of this technique ideally as a living document that will be updated regularly.

Keywords Adolescent idiopathic scoliosis · Vertebral body tethering · Literature review

Introduction

Adolescent Idiopathic Scoliosis (AIS) is the most common pediatric spinal curvature, affecting 2–3% of children between the ages of 10–18 years.[1] For severe AIS, the standard of care is spinal arthrodesis or fusion. Although fusion is associated with good short and intermediate-term outcomes, there are a number of potential long-term drawbacks resulting from elimination of motion and stiffening of the spine within operated segments. These consequences include disk degeneration caudal or cephalad to the fusion mass, loss of remaining spine growth potential, and significant back pain, especially over the long term.[2–5] Moreover, return to preoperative level of athletic activity is negatively impacted as the distal level of fusion becomes more caudal.[4] Spinal fusion is a non-physiological solution for the treatment of deformed but otherwise healthy motion segments in the adolescent with idiopathic scoliosis.

Vertebral Body Tethering (VBT) is a non-fusion alternative to anterior or posterior spinal fusion (PSF). VBT is performed via an anterior approach. The procedure was first reported in 2010 by Crawford et al. who performed a thoracic tether in an 8-year-old boy who did well up to 48 months follow-up (FU) and demonstrated for the first time the clinical application of growth modulation in which correction occurred steadily over time.[6] For skeletally immature patients for whom VBT is indicated, the procedure capitalizes on the Hueter-Volkmann principle.[7–9] Optimal indications have yet to be delineated and may vary by patient preferences and surgical technique, but the current consensus is the procedure best indicated for skeletally immature patients with flexible, moderate thoracic, or thoracolumbar/lumbar curvatures up to 65 degrees. Controversially, some surgeons have advocated for the treatment of patients who have surpassed the adolescent growth spurt, and others have

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utilized disk releases to address more severe and rigid curvatures. The use of double-row tethers has been promoted, particularly in the lumbar spine in order to achieve better corrections and improve the longevity of the tether construct. Others have performed bilateral tether procedures for double major curvature and still others have offered hybrid fusion tether constructs in which larger thoracic curvatures are treated with traditional fusion and the lumbar spine is tethered. There have been few or no reports to date on these variations. Since the procedure gained regulatory approval only relatively recently, there have been relatively few publications on the radiographic, health-related quality of life, and complication outcomes of the procedure; however, there is an increasing tempo of publications more recently as experience and follow-up accrue across centers. Comparisons to the standard of care PSF are ultimately required for which there have been some publications including assessment of range of motion and trunk endurance.[10–20,21] There is a need for a comprehensive review of outcomes of VBT particularly in relation to clinical success, reoperation rates, and other complications, the learning curve, and the impact of cord breakage on outcomes. It is imperative for surgeons performing this procedure to have a mastery of the current literature including historical and current challenges and pitfalls as well as best practices in order to optimize outcomes by improving indications and technical aspects of the approach as this paradigm-shifting procedure gains broader adoption. Through an in-depth understanding of the current knowledge base and its deficiencies, surgeons and researchers can work collectively to define appropriate indications, best surgical techniques, and areas for possible innovation of this procedure and the implants utilized and will assist the surgeon and patient/family unit in shared decision-making. We conduct a comprehensive review of the available VBT literature and report on radiographic outcomes, complications, and anesthetic considerations. This will be the most comprehensive literature review to date with strict inclusion criteria to optimize the quality of data included.

Methods

To examine the current body of literature on VBT, we utilized PubMed, Scopus, and Web of Science databases. We queried PubMed using the keywords “vertebral body tether” OR “Anterior vertebral body tether” OR “Anterior vertebral tethering” and vertebral body tether OR Anterior vertebral body tether OR Anterior vertebral tethering. For the Scopus and Web of Science searches, we utilized “vertebral body tether” OR “Anterior vertebral body tether” OR “Anterior vertebral tethering” and “vertebral body tether” OR “Anterior vertebral body tether” OR “Anterior vertebral tethering.” Our query yielded 245 publications on PubMed, 121 on Scopus, and 178 on Web of Science. These were manually filtered to 49 publications based on our inclusion criteria: topic of VBT, either basic science or clinical human studies, and minimum 2-years post-op follow-up for clinical studies. Reviews, letters, and case reports were excluded. Additionally, we reviewed the reference sections of each of the 49 publications to search for additional studies that may have been missed in our initial queries, but no others were found. All basic sciences findings were summarized and assessed in the appendix. Publication dates for included studies ranged from April 2002 to December 2022.

Human clinical studies

The following data represent a cumulative overview of the 26 studies that reported minimum 2-year results between 2014 and December, 2022 on 1,366 patients with idiopathic scoliosis who underwent Vertebral Body Tethering (VBT).[10–18,22–38] Mean age ranged between 11.0 and 15.0 years. Mean follow-up was between 20.1 and 64.5 months. 12 studies reported the Lenke classification, which included all curve types being represented by the conglomerate of studies (Table 1).

Radiographic Outcomes

19 studies reported thoracic curve measurements for major thoracic curvature, with cases utilizing VBT for the thoracic curve only or bilateral VBT which included the TL/L compensatory curvature.[10,12–17,20,22,25–34] Mean preoperative thoracic curvature ranged from 40.1° to 56.5° which corrected to 11.2°–38.0° at first erect X-ray and 9.0°–35.0° at final follow-up. Percent correction of the major thoracic curve ranged from 19.7 to 82.0%. The proximal thoracic curve was measured in 10 studies, with mean preoperative curve 20.0°–31.5°. Curves corrected to 10.0°–24.0° at final follow-up. Percent correction ranged from 23 to 51.0%. 15 studies reported on the compensatory lumbar curvature. Mean preoperative curve ranged from 23.7° to 49.0° which corrected to 6.8°–30.0° at final follow-up. Percent correction was between 7.1 and 82.0%. Only five of the studies reported on global coronal alignment. The mean preoperative coronal alignment ranged from 1.1 to 2.3 cm which corrected to −0.7 to 1.4 cm at final follow-up (Table 2). There have been no studies of thoracolumbar/lumbar major curve types only although several studies did include some patients with TL/L major curves. No studies have been published specifically assessing bilateral tether constructs for double curves although some studies did include patients with bilateral tether surgery.[18]

Distinct definitions of “clinical success” following VBT have been utilized to assess radiographic correction.

Table 1 Clinical human study characteristics and preoperative Lenke classification

Author (year)	Number of patients	Mean age (years)	Mean follow-up	Lenke curve (1:2:3:4:5:6)
Abdullah et al. [22]	120	12.6	24 months	N/A
Baker et al. [20]	17	12.9	33 months	(9:3:1:0:4:0)
Baroncini et al. [25]	86	13.2	24 months	N/A
Hoernschemeyer et al. [17]	29	12.7	38.4 months	(23:1:1:0:4:0)
Miyanji et al. [29]	57	12.7	40.4 months	(48:6:1:0:1:1)
Newton et al. [15]	17	11.0	30.0 months	N/A
Newton et al. [16]	23	12.0	40.8 months	N/A
Pehlivanoglu et al. [13]	21	11.0	27.4 months	N/A
Pehlivanoglu et al. [14]	13	11.8	36.4 months	N/A
Rushton et al. [12]	112	12.7	37.0 months	(85:15:5:2:3:2)
Samdani et al. [31]	11	12.0	24.0 months	(11:0:0:0:0:0)
Samdani et al. [32]	57	12.4	55.2 months	(57:0:0:0:0:0)
Wong et al. [10]	5	11.7	48.0 months	(5:0:0:0:0:0)
Von Treuheim et al. [33]†	19	15.0	25.0 months	(14:4:1:0:0:0)
	16	12.5	24.0 months	(15:1:0:0:0:0)
Yucekul et al. [34]	25	12.0	38.6 months	(25:0:0:0:0:0)
Bernard et al. [26]†	10	14.9	56.6 months	N/A
	10	12.5	64.5 months	N/A
Meyers et al. [27]	49	15.0	32.5 months	(23:1:5:0:19:1)
Miyanji et al. [28]	50	11.9	25.2 months	(43:7:0:0:0:0)
Newton et al. [30]	237	12.1	26.4 months	N/A
Alanay et al. [23]	30	12.3	20.1 months	N/A
Shankar et al. [11]	69	14.0	25.0 months	(33:3:6:1:20:6)
Eaker et al. (2022)	35	14.2	N/A	N/A
Chen et al. [36]	35	15.5	N/A	N/A
Ergene et al. [18]	56	12.6	N/A	N/A
Baroncini et al. [37]	90	14.6	24.0 months	N/A
Mathew et al. [38]	67	13.2	N/A	N/A

†Skeletally mature and immature patients recorded in top and bottom rows, respectively

Newton et al. recently reported a retrospective review that defined clinical success through two criteria: achieving a major curve below 35° and having no indication for a PSF.[30] Similarly, Hoernschemeyer et al. indicated that a procedure was successful if there was no PSF, and if the Cobb angles were ≤ 30° when assessed at skeletal maturity.[17] Other clinicians have defined clinical failure as the need for revision surgery.

16 of the studies reported on thoracic kyphosis and lumbar lordosis.[10,12–16,20,22,25,27,29–34] Mean preoperative thoracic kyphosis ranged from 6.3° to 30.7° which corrected to 17.0°–33.0° at final follow-up. Mean preoperative lumbar lordosis of 55.4°–60.5° preoperatively, remained relatively stable from − 56.5° to 55.5° at final follow-up. Five studies reported on global sagittal alignment.[13,14,25,31,32] Mean preoperative sagittal alignment ranged from 0.5 to 3.1 cm preoperatively and -8.8 to 1.8 cm at final follow-up (Table 3).

Nineteen studies reported on skeletal maturity and one study assessed peak height velocity.[10,12–17,20,22,25–34] Specifically, 11 studies reported on Sanders scores, 18 reported on Risser stage, and 2 reported Proximal Humerus Ossification System (PHOS) stage in addition to Risser. Mean preoperative Sanders score was 3.08 (range 1–7), while mean FU Sanders score was 6.9 (range 3–8); however, only three studies reported a postoperative Sanders score. The mean preoperative Risser stage was 1.01 (range 0–5), while the mean postoperative Risser stage was 4.3 (range 0–5). At the time of surgery, the triradiate cartilage was closed in 5.9–100% of all patients within each specific study. Assessment of outcomes must be further understood based on stratification by skeletal maturity which will be discussed below.

A single surgeons series by Newton et al. in 2020 directly compared outcomes in patients who underwent VBT vs patients who underwent PSF for thoracic major curve types.[16] 23 VBT patients were compared to 26 PSF. Preoperative main thoracic curve measurements between the two groups were similar (53° ± 8° for the VBT group and 54° ± 7°

Table 2 Radiographic Outcomes in Coronal Plane

Author	Data reported	Curve Types	Proximal thoracic curve (degrees)				Main thoracic curve (degrees)				Lumbar curve (degrees days)				Coronal balance (cm)		
			Pre-op	F.E	FU	Cx (%)	Pre-op	F.E	FU	Cx (%)	Pre-op	F.E	FU	Cx (%)	Pre-op	F.E	FU
Abdullah et al. [22]	Mean (95% Cl)	Th major	N/A	N/A	N/A	N/A	51.2 (49.7–52.7)	26.9 (25.3–28.5)	27.5 (25.2–29.7)	46.3	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Baker et al. [24]	Mean ± SD	Th major, TL/L	N/A	N/A	N/A	N/A	45.0 ± 7	27.0 ± 9	20 ± 26	55.0	28.0 ± 7	24 ± 7	26 ± 13	7.1	N/A	N/A	N/A
Baroncini et al. [25]	Mean ± SD	Th major, TL/L	N/A	N/A	N/A	N/A	52.4 ± 13.9	N/A	28.5 ± 13.6	45.6	47.6 ± 14.3	NR	26.6 ± 12.7	44.1	N/A	N/A	N/A
Hoern-schemeyer et al. [17]	Mean ± SD	Th major, TL/L	N/A	N/A	N/A	N/A	50 ± 7	21 ± 9	9 ± 17	82.0	49 ± 6	15 ± 8	21 ± 15	57.1	N/A	N/A	N/A
Miyanji et al. [29]	Mean ± SD	PTR, Th major, TL/L	31.5 ± 9.5	21.9 ± 10.6	22.3 ± 14.3	41.8	51.0 ± 10.9	24.6 ± 11.8	23.0 ± 15.4	42.9	33.0 ± 12.7	24.0 ± 14.1	28.0 ± 8.5	15.2	N/A	N/A	N/A
Newton et al. [15]	Mean ± SD	PTR, Th major, TL/L	31 ± 8	22 ± 7	21 ± 10	32.3	52 ± 10	31 ± 10	27 ± 20	51.0	33 ± 10	24 ± 8	28 ± 16	14.7	N/A	N/A	N/A
Newton et al. [16]	Mean ± SD	PTR, Th major, TL/L	31 ± 9	24 ± 8	24 ± 13	23.0	53 ± 8	34 ± 8	33 ± 18	43.0	34 ± 8	26 ± 7	30 ± 12	61.3	1 ± 1	1.2 ± 1	1.3 ± 1
Pehlivanoglu et al. [13]	Mean (range)	PTR, Th major, TL/L	20.4 (18.4–24.2)	14.3 (13.1–15.2)	14.9 (13.8–15.6)	27.0	48.2 (44.0–52.1)	16.2 (14.6–18.1)	10.1 (7.7–11.2)	79.0	24.8 (22.4–28.1)	17.6 (14.4–28.1)	9.6 (8.4–10.1)	82.0	1.9 (−6.0–2.4)	1.5 (−0.4–1.7)	0.8 (−0.6–1.2)
Pehlivanoglu et al. [14]	Mean (range)	PTR, Th major, TL/L	20.0 (17.0–24.0)	15.0 (12.0–16.0)	13.0 (12.0–15.0)	35.0	48.0 (43.0–54.0)	17.0 (15.0–19.0)	10.0 (7.0–11.0)	80.0	45.0 (44.0–47.0)	14.0 (12.0–15.0)	8.0 (5.0–10.0)	41.6	2.1 (−0.4–2.5)	1.4 (−0.2–1.8)	0.5 (−0.2–1.3)
Rushton et al. [12]	Mean ± SD	Th major	N/A	N/A	N/A	N/A	50.8 ± 10.2	26.6 ± 10.1	25.7 ± 16.3	49.6	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Samdani et al. [31]	Mean ± SD	PTR, Th major, TL/L	21.2 ± 10.8	13.4 ± 12.3	15.4 ± 14.1	27.4	44.2 ± 9.0	20.3 ± 11.0	13.5 ± 11.6	70.0	25.1 ± 8.7	14.9 ± 4.9	7.2 ± 5.1	33.8	1.6 ± 1.4	1.6 ± 1.6	1.3 ± 6.5
Samdani et al. [32]	Mean ± SD	PTR, Th major, TL/L	25.0 ± 5.7	20.1 ± 5.5	17.9 ± 6.4	28.4	40.4 ± 6.8	19.3 ± 8.4	18.7 ± 13.4	53.7	23.7 ± 6.1	15.2 ± 6.1	15.7 ± 8.4	76.0	2.4 ± 14.8	-2.5 ± 15.6	-0.7 ± 15.8
Wong et al. [10]	Mean	PTR, Th major, TL/L	20.4	15.5	10.0	51.0	40.1	31.0	32.2	19.7	31.5	13.0	15	52.4	N/A	N/A	N/A
Von Treuheim et al. [33]†	Mean (range)	Th major, TL/L	N/A	N/A	N/A	N/A	49.0 (40–69)	29.0 (13–46)	29.0 (12–42)	69.4	31.5 (9–47)	13.0 (3–33)	15 (0–31)	58.4	N/A	N/A	N/A
		Th major, TL/L	N/A	N/A	N/A	N/A	51.0 (36–69)	23.5 (4–36)	15.0 (−16–38)	70.5	32.5 (17–52)	13.0 (−6–29)	13.5 (−17–27)	15.2	N/A	N/A	N/A

Table 2 (continued)

Author	Data reported	Curve Types	Proximal thoracic curve (degrees)				Main thoracic curve (degrees)				Lumbar curve (degrees days)				Coronal balance (cm)		
			Pre-op	F.E	FU	Cx (%)	Pre-op	F.E	FU	Cx (%)	Pre-op	F.E	FU	Cx (%)	Pre-op	F.E	FU
Yucekul et al. [34]	Mean ± SD	Th major, TL/L	N/A	N/A	N/A	N/A	46.0 ± 7.7	23.3 ± 5.9	12.0 ± 11.5	73.9	28.2 ± 7.5	15.9 ± 8.2	6.8 ± 10.4	75.9	N/A	N/A	N/A
Bernard et al. [26]†	Mean (range)	Th major	N/A	N/A	N/A	N/A	56.5 (40–79)	11.2 (3–24)	20.0 (9–45)	67.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		Th major	N/A	N/A	N/A	N/A	47.4 (40–58)	20.3 (2–33)	19.4 (− 17–56)	59	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Meyers et al. [27]	Mean ± SD	PTR, Th major	15.8 ± 11.1	N/A	12.4 ± 7.5	21.5	41.6 ± 12.9	N/A	22.5 ± 8.7	45.9	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Miyanji et al. [28]	Mean ± SD	PTR, Th major, TL/L	22.8 ± 8.8	16.8 ± 8.8	13.1 ± 7.5	42.5	49.4 ± 8.5	27.1 ± 8.5	24.9 ± 9.5	49.6	32.7 ± 6.9	25.0 ± 7.0	21.3 ± 7.9	34.9	N/A	N/A	N/A
Newton et al. [30]	Mean ± SD	Th major, TL/L	N/A	N/A	N/A	N/A	48.0 ± 9.0	N/A	27.0 ± 12.0	43.8	30.0 ± 8.0	N/A	21.0 ± 10.0	30.0	N/A	N/A	N/A

F.E. first erect, *FU* follow-up, *Cx* correction, *PTR* proximal thoracic curve, *Th major* thoracic major, *TL/L major* thoracolumbar/lumbar

[*] Of the 6 included patients, only four patients were followed up after two years; follow-up data reflects results from 4/6 patients

[†] Skeletally mature and immature patients recorded in top and bottom rows, respectively

Table 3 Radiographic Outcomes in Sagittal Plane (only studies that reported sagittal outcomes are included)

Author	Thoracic Kyphosis (°)			Lumbar Lordosis (°)			Sagittal Balance (cm)		
	Pre-op	F.E	FU	Pre-op	F.E	FU	Pre-op	F.E	FU
Abdullah et al. [22]	28.5 (95% Cl 26.4–30.6)	27.4 (95% CI 25.4–29.5)	29.2 (95% CI 26.5°–31.0°)	N/A	N/A	N/A	N/A	N/A	N/A
Baker et al. [24]	20 ± 12	20 ± 15	17 ± 13	59 ± 11	54 ± 12	52 ± 13	N/A	N/A	N/A
Baroncini et al. [25]	28.3 ± 13.8	N/A	33.0 ± 13	47.5 ± 13.1	N/A	48.4 ± 13.5	0.5 ± 3.1	N/A	−0.4 ± 2.8
Miyanji et al. [29]	18.7 ± 11.1	18.7 ± 12.0	22.0 ± 13.3	−55.4 ± 11.3	−53.6 ± 11.6	−56.5 ± 12.1	N/A	N/A	N/A
Newton et al. [15]	25 ± 13	22 ± 14	22 ± 10	N/A	N/A	N/A	N/A	N/A	N/A
Newton et al. [16]	24 ± 12	22 ± 12	19 ± 13	N/A	N/A	N/A	N/A	N/A	N/A
Pehlivanoglu et al. [13]	26.8 (21.4–36.1)	25.3 (20.8–35.6)	26 (20.1–31.8)	51.3 (43.4–58.1)	49.9 (41.5–56.1)	51.8 (42.5–55.3)	1.2 (−0.4–1.7)	0.9 (−1.3–1.4)	0.4 (−0.3–1.1)
Pehlivanoglu et al. [14]	26 (21–36)	24 (21–34)	26 (20–31)	50 (45–57)	48 (41–56)	52 (41–55)	1.3 (−0.5–1.9)	0.8 (−1.1–1.3)	0.6 (−0.4–1.2)
Rushton et al. [12]	18.6 ± 11.4	18.8 ± 11.8	21.4 ± 13.0	N/A	N/A	N/A	N/A	N/A	N/A
Samdani et al. [31]	20.8 ± 13.3	13.5 ± 8.7	21.6 ± 12.7	47.5 ± 10.6	38.4 ± 9.2	54.9 ± 13.1	3.1 ± 2.0	5.9 ± 3.8	1.8 ± 0.9
Samdani et al. [32]	15.5 ± 10.0	17 ± 10.1	19.6 ± 12.7	51.9 ± 11.4	50.9 ± 10.6	54.4 ± 11.8	2.6 ± 26.7	3.8 ± 29.1	−8.8 ± 30.1
Von Treuheim [33]†	19.0 (4–38)	17.0 (4–35)	20.0 (1–45)	N/A	N/A	N/A	N/A	N/A	N/A
	23.5 (12–38)	21.5 (10–37)	23.5 (15–41)	N/A	N/A	N/A	N/A	N/A	N/A
Wong et al. [10]	16	N/A	17.8	46.8	N/A	52.2	N/A	N/A	N/A
Yucekul et al. [34]	30.7 ± 10.5	28.2 ± 10.4	30.5 ± 9.1	60.5 ± 11.3	55.8 ± 11.4	54.9 ± 10.2	N/A	N/A	N/A
Meyers et al. [27]	22.2 ± 11.1	N/A	25.6 ± 13.4	55.4 ± 12.5	N/A	56.0 ± 12.4	N/A	N/A	N/A
Newton et al. [30]	18.0 ± 12.0	NA	19.0 ± 13.0	−59 ± 15	NA	−57 ± 13	N/A	N/A	N/A

†Skeletally mature and immature patients recorded in top and bottom rows, respectively

for the PSF group ($p = 0.4$)). Final follow-up revealed better coronal plane correction for PSF (33° ± 18° for VBT compared with 16° ± 6° for the PSF group ($p < 0.001$). Nine patients in the VBT cohort underwent revision procedures as compared to none in the PSF group. The patients in the VBT group were less skeletally mature than the PSG group although the groups matched fairly closely otherwise prior to surgery.

A more recent multicenter study by Newton et al. provided a comparison of VBT versus PSF with a much larger cohort than the previous comparison.[30] 237 VBT patients were propensity score matched to 237 PSF patients using age, sex, Risser, and preoperative thoracic curve as covariates. Mean FU was just over 2 years. Patients in the VBT cohort had a mean main thoracic curvature of 27° ± 12° at latest FU, from 48 ± 9° preoperatively. PSF patients had a decreased ($p < 0.001$) curve of 20° ± 7° at latest follow-up from a larger preoperative curve of 53 ± 8° compared to VBT. 76% of VBT patients and 97.4% of PSF patients were deemed clinically successful at final follow-up, defined as thoracic major curve measuring less than 35° ($p < 0.001$) and no indication for fusion. Moreover, 16% of patients in the VBT group required 46 subsequent revisions. 6.2% of VBT patients had conversion to PSF and 5.9% had revision surgery due to overcorrection. Only 1.3% (3 patients) in the PSF group required 4 subsequent reoperations ($p < 0.01$).

Tether breakage, either confirmed or suspected, was found in 19.8% of VBT cases.

Skeletal maturity

The rationale for VBT is based on the potential for growth modulation in the skeletally immature patient via Hueter-Volkmann. Optimal timing for surgery requires curve size, flexibility, and growth potential assessment. VBT for large curves with little remaining growth will likely not result in ideal correction, similarly a small curve with abundant remaining growth will likely lead to overcorrection. Several studies in our review have reported on skeletally mature patients with favorable postoperative and follow-up outcomes when compared to skeletally immature patients.[10,12–17,20,25,26,29,31,33,34] (Table 4).

Timing of intervention in terms of skeletal maturity is crucial as suggested by a comparison of outcomes between similar patient cohorts reported by Newton and Hoernschemeyer et al.[15,17] The mean preoperative Risser stage was 0 in Newton's cohort and 1.9 in Hoernschemeyer's. In the former series, 94% of the patients had open triradiate cartilage versus 38% in the latter study. Despite similar preoperative major curves, Newton's cohort reported a smaller curve correction to a final curvature of 27° ± 20° versus 9° ± 17° in Hoernschemeyer group. Furthermore, a higher reoperation rate was reported in Newton's vs. Hoernschemeyer's cohort (41% vs. 21%, respectively). Specifically in Newton's cohort, 23.5% patients were converted to PSF and 4 23.5% patients underwent tether removal secondary to complete correction or overcorrection, whereas in Hoernschemeyer's cohort, 10.3% of patients required PSF and 3.4% underwent a tether extension. These findings suggest less predictable

Table 4 Assessments of skeletal maturity

Author (year)	Mean sanders (range)		Mean Risser (range)		Mean Proximal Humerus Ossification System (PHOS) stages		Triradiate cartilage status
	Preoperative	Last follow-up	Preoperative	Last follow-up	Preoperative	Last follow-up	At surgery
Abdullah et al. [22]	NR	NR	0.91 (0–3)	NR	NR	NR	NR
Baker et al. [24]	3.2 (2–5)	6.3 (3–8)	0.2 (0–3)	3.4 (0–5)	NR	NR	NR
Baroncini et al. [25]	NR	NR	1.8 (0–4)	NR	NR	NR	NR
Hoernschemeyer et al. [17]	NR	NR	N/A	NR	NR	NR	38% Closed
Miyanji et al. [29]	3.3 (SD 1.2)	NR	0.5 (0–3)	4.3 (0–5)	NR	NR	NR
Newton et al. [15][††]	(1–4)	NR	0.0 (0–0)	(0–4)	NR	NR	6% Closed
Newton et al. [16]	2.5 (2–3)	NR	0.1 (0–1)	3.9 (2–5)	NR	NR	22% Closed
Pehlivanoglu et al. [13]	3.1 (2–4)	NR	0.4 (0–2)	NR	NR	NR	NR
Pehlivanoglu et al. [14]	3.2 (2–4)	NR	0.4 (0–2)	NR	NR	NR	38% Closed
Rushton et al. [12]	3.4 (2–6)	NR	0.5 (0–3)	(0–5)	NR	NR	NR
Samdani et al. [31]	3.4 (NR)	NR	0.6 (NR)	NR	NR	NR	NR
Samdani et al. [32]	3.1 (2–5)	7.5 (NR)	0.5 (0–4)	4.2 (NR)	NR	NR	NR
Von Treuheim [33][†]	NR	NR	4 (3–5)	5 (4–5)	2.5 (1–3)	4 (1–5)	100% Closed
	NR	NR	1.5 (0–2)	4 (1–5)	4 (2–5)	5 (4–5)	79% Closed
Wong et al. [10]	2.6 (2–5)	NR	0.0 (0–0)	NR	NR	NR	60% Closed
Yucekul et al. [34]	3.0 (1–7)	7.0 (5–8)	0 (0–4)	5.0 (3–5)	NR	NR	NR
Bernard et al. [26][†]	NR	NR	3.6 (3–5)	NR	NR	NR	100% Closed
	NR	NR	0.6 (0–2)	NR	NR	NR	60% Closed
Meyers et al. [27]	NR	NR	3.83 (3–5)	NR	3.73 (3–5)	NR	5.9% Closed
Miyanji et al. [28]	NR	NR	0.5 (0–3)	NR	NR	NR	61% Closed
Newton et al. [30]	NR	NR	Risser 0–1: 79% Risser 1: 8% Risser 2–3: 19% Risser 4 to 5: 2%	NR	NR	NR	41% Closed

[†] Skeletally mature and immature patients recorded in top and bottom rows, respectively

[††] Study only reported ranges

outcomes in less skeletally mature patients with open triradiate cartilages although stratification of outcomes by skeletal maturity in larger cohorts will be helpful. Furthermore, machine-learning algorithms may prove beneficial for a more complete understanding of the interplay between skeletal maturity, curve magnitude and flexibility, levels to be included, as well as tensioning strategies.

Alanay et al. stratified outcomes based on Sanders scores (ranging from 1 to 7) in flexible thoracic curves < 70°.[23] They found a significant increase in height for Sanders 1 patients (17 cm) compared to Sanders 2, 3, 4–5, and 6–7 groups (13 cm, 5 cm, 3 cm, and 1 cm, respectively) at 39-months follow-up ($p < 0.001$). Median radiographic length gain ($p < 0.001$) and curve correction ($p = 0.009$) also differed among the groups, suggesting that optimal timing for VBT may be after Sanders 2. Larger studies with longer follow-up are needed to corroborate these findings.

Von Treuheim et al. compared thoracic VBT outcomes between skeletally immature (IM, Risser 0–2) and mature (M, Risser 3–5) patients.[33] Despite similar initial curve magnitudes (51° and 49°) in both groups, a significant difference in curve magnitude (15° in IM vs. 29° in M, $p = 0.008$) was noted at final FU. The IM group demonstrated greater curve correction (69% vs. 53%, $p = 0.008$) and higher clinical success (94% vs. 79%) with similar SRS outcome scores at follow-up. This study suggests clinical feasibility of VBT in some skeletally mature patients, but long-term results are needed.

In a smaller but similar series, Bernard et al. analyzed the operative outcomes of 10 skeletally immature (IM, Risser, 0–2) and 10 skeletally mature (M, Risser 3–5) patients.[26] There were three double curves in each group, and two lumbar-only curves in the skeletally mature group. Mean major curve for immature was 47.4° (40°–58°) versus mature 56.5° (40°–79°). Final curve magnitude was for immature was 11.2° (3°–24°) and 20° (9°–45°) for mature. These two series suggest satisfactory outcomes can be achieved after VBT in select skeletally mature patients at 2 years following surgery although longer-term FU is imperative.

Meyers et al. evaluated VBT in 49 skeletally mature patients (Risser 3–5).[27] The study showed a 76% clinical success rate, defined as achieving major curvature less than 30° and no indication for PSF, after an average follow-up of 32.5 months. Patients with major thoracic and major thoracolumbar curves demonstrated significant improvement in Cobb magnitude (48% and 59% correction, respectively, $p < 0.01$). Patients with clinically unsuccessful outcomes had larger preoperative Cobb magnitudes ($p < 0.01$) and less curve flexibility ($p = 0.06$). This series suggests good intermediate outcomes can be expected for select skeletally mature patients with moderate and flexible curves.

Body shape and health-related quality of life

Six studies included assessment of rotational deformity via inclinometer measurements.[13–16,22,31,32] Mean preoperative thoracic inclinometer ranged from 12.4° to 16.0 decreasing rotation to 6.0°–12.0° (25.0–57.2% correction). Compensatory curve lumbar inclinometer ranged from 5.0° to 7.0° preoperatively and 2.0° to 8.0° (− 14.3–60.0% correction) at follow-up (Table 5). There were no studies that included primarily thoracolumbar/lumbar major curvatures for which inclinometer measurements were provided.

Shoulder balance, an important parameter for body image and overall patient satisfaction, has been studied by Miyanji et al. in 50 patients with Lenke 1 or 2 curve types who underwent VBT.[28] Preoperatively, the mean proximal thoracic and main thoracic curves were 22.8° ± 8.8° and 49.4° ± 8.5°, respectively. At a mean follow-up of 2.1 years, these curves improved to 13.1° ± 7.5° and 24.9° ± 9.5°, respectively. Radiographic shoulder height (RSH) was used to assess shoulder balance. Preoperatively, 70% of patients had acceptable shoulder balances, 28% had moderate imbalance, and 2% had severe imbalance. At follow-up, 84% of patients had acceptable shoulder balance and 16% had moderate imbalance, indicating that VBT can improve shoulder imbalance over the long term. Comparison of shoulder balance between patients treated with PSF versus is VBT has not yet been published.

Six studies evaluated patient-reported outcomes with the Scoliosis Research Society 22-Item Questionnaire (SRS-22).[14,26,27,30,34,39] The mean preoperative and postoperative SRS scores were 3.7 (2.5–4.9) and 4.4 (2.4–5.0),

Table 5 Inclinometer measurements

Author (Year)	Thoracic Axial Rotation (°)			Lumbar Axial Rotation (°)		
	Pre-op	Follow-up	% Correction	Pre-op	Follow-up	% Correction
Newton et al. [15]	15.0	10.0	33.3	5.0	2.0	60.0
Newton et al. [16]	16.0	12.0	25.0	7.0	8.0	-14.3
Pehlivanoglu et al. [13]	14.8	6.6	55.4	N/A	N/A	N/A
Pehlivanoglu et al. [14]	14.0	6.0	57.2	N/A	N/A	N/A
Samdani et al. [31]	12.4	6.9	44.4	N/A	N/A	N/A
Samdani et al. [32]	13.6	8.6	36.7	N/A	N/A	N/A

respectively (Table 6). The total score improved across all studies with surgery. In a comparative study of PSF versus VBT by Newton et al. in patients with Lenke 1 curvature (2022), similar outcomes were achieved in both cohorts[30]. These difference do not meet the minimal clinically important difference.[40]

Complications

Based on 654 patients in 16 studies that included reporting of complications following VBT, the below information is provided.[10–18,22,24,26,27,31–33]

Approach-related complications

Approach-related complications were recorded as pulmonary, vascular, and visceral complications following VBT. Pulmonary complications were reported in 36 (7.0%) patients across the 11 studies that reported pulmonary complications, ranging from 3.3 to 80% of total patients within each study. Among the studies documenting pulmonary complications, the following percentages were observed: atelectasis (1.5% of cases), pneumothorax (0.9% of cases), pleural effusion and pneumonia (0.7% of cases each), chylothorax (0.6% of cases), hemothorax or mucus plugs (0.4% of cases each), and perihilar effusion (0.2% of cases). Other approach-related complications were reported in 3.2% of patients across seven studies. Specifically, 0.7% developed paresthesia, and 0.2% experienced hematuria, Horner syndrome, syncope, radiculopathy, and keloid formation, respectively (Table 7). Furthermore, a single case of ureteral injury in a lumbar VBT procedure has been reported.[41] This was treated with a ureteral stent that was removed 3 months later. At most recent follow-up, the patient was recovering well. Meyers et al. showed that patients who underwent rib resection for thoracoplasty or to facilitate placement of implants were found to have a greater likelihood of hemothorax and other pulmonary complications versus those who did not (18.2% vs 4.9%, $p = 0.04$).[42] The authors no longer utilize thoracoplasty in conjunction with VBT. In that study, the authors reported a case of Raynaud phenomenon in both the upper and lower extremities, ipsilateral to the approach.

Table 6 SRS scores

Author	Preoperative SRS Score	YR2 SRS Score
Newton et al. [16]	4.2 (3.4–4.9)	4.4 (3.6–4.9)
Newton et al. [30]	4.1 (2.5–4.7)	4.0 (2.4–4.9)
Pehlivanoglu et al. [14]	2.9 (2.6–3.1)	4.8 (4.6–5.0)
Yucekul et al. [34]	4.0 (3.4–4.5)	4.3 (3.9–4.8)
Bernard et al. [26]	3.5 (2.5–4.1)	4.3 (3.5–5.0)
Meyers et al. [27]	3.8 (3.3–4.3)	4.2 (3.8–4.6)

Procedure-related complications

Procedure-related complications were reported across 16 of the 17 studies that commented on complications. 14 studies specifically analyzed tether breakage, in which 118 of the 566 (20.8%) (range 0–36%) patients had presumed or confirmed tether breakages with mean follow-up of 32.4 months (20.1–64.5 months). Furthermore, 16 studies (628 total patients) reported on reoperation rates. Specifically, 8.3% of patients underwent revision surgery, in which 2.4% had reoperations due to tether breakage and 4.9% for overcorrection. 2.4% of patients underwent a conversion to a PSF either due to tether breakage or overcorrection. There were 37 (5.7%) other reported procedure-related complications including 4 cases of CSF leak from screw impingement, 4 cases of overcorrection, 3 cases of screw displacements due to breakage ($n = 2$) and loosening ($n = 1$), and one case of radiculopathy from a screw tip causing nerve root impingement in a contralateral lumbar foramen within a TL construct (Table 7).

Two studies specifically assessed the effects of tether breakage on clinical outcomes. Shankar et al., assessed tether breakage in a single surgeon series of 69 patients.[11] A tether breakage (TB) rate of 27% at the two years FU was reported. TB occurred predominantly in major curves (70%) for cases in which bilateral procedures of both thoracic and TL/L curves were performed. Thoracolumbar curve TB rate was 32% versus 8% for thoracic tethers ($p = 0.003$). 75% of the breakages occurred in TL/L major curvatures compared to the 25% in thoracic major. Similarly, Meyers et al. reported tether-related complications following VBT in patients who were approaching skeletal maturity at the time of their surgery.[27] 41% of the patients in the cohort demonstrated tether cord breakage, with 6% of patients having breakage at two levels at mean 32.5 months FU. Despite this, no differences in clinical success (residual major curves ≤ 30° and no spinal fusion) were found between those with or without TB.

One study analyzed complications based on the patient's skeletal maturity. Alanay et al. reported 12 (38.7%) procedure-related complications in their cohort of 31 patients that were stratified by their Sanders score (2–7).[23] Mechanical complications and overcorrections were found to be significantly higher in the Sanders 2 group. Sixty percent of Sanders 2 patients demonstrated mechanical complications compared to only 7.7% of Sanders 3 patients. Furthermore, 80% of Sanders 2 patients had overcorrections when only 7.7% of Sanders 3 patients reported such outcomes. There were no mechanical complications or overcorrections in Sanders 4–7 maturity.

Table 7 Complications

Author	Patients in cohort	Mean age (years)	Tether breakage (%)	Pulmonary complications (%)	Reoperations (%)				Other (%)
					Tether Breakage	Operation(s)	Overcorrection	Operation(s)	
Samandi et al. [31]	11	12.0	0 (0.0)	1 (9.0)	0 (0.0)	NR	2 (18.2)	2 Cases of distal 3 screws retightened	0
Newton et al. [15]	17	11.0	1 (5.9)	2 (11.8)	1 (5.9)	1 Tether replacement	4 (23.5)	4 Tether removals	0
Ergene et al. [18]*	56	12.6	NR	6 (10.7)	NR	NR	NR	NR	0
Wong et al. [10]*	5	11.7	NR	4 (80.0)	NR	NR	2 (40.0)	2 Conversions to PSF	1 (20.0) – Hematuria
Newton et al. [16]	23	12	12 (52.2)	1 (4.3)	2 (8.7)	1 Retethering 1 Conversion to PSF	5 (21.7)	3 Tether Removals 1 Tether Replacement 1 Retethering	1 (4.3) – Horner Syndrome
Pehlivanoglu et al. [13]	21	11.0	1 (4.8)	1 (4.8)	1 (4.8)	1 Tether removal	0 (0.0)	NR	0
Hoernschemeyer et al. [17]	29	12.7	14 (48.0)	1 (3.4)	2 (6.6)	2 Conversions to PSF	3 (10.3)	2 Conversions to PSF 1 Tether extension	1 (3.4) – Syncope
Baker et al. [24]	17	12.9	9 (47.0)	0 (0.0)	1 (5.9)	1 Tether replacement	2 (11.8)	2 Conversions to PSF	0
Rushton et al. [12]	112	12.7	36 (32.0)	9 (8.0)	5^{**} (4.5)	2 Tether replacements 3 Conversions to PSF	5 (4.5)	5 Tether removals	4 (3.6) – 2 CSF leaks 1 Wound infection 1 GI infection
Pehlivanoglu et al. [14]	13	11.8	0 (0.0)	3 (23.1)	0 (0.0)	No tether breakages	0 (0.0)	No overcorrections	0
Abdullah et al. [22]	120	12.6	2 (1.7)	4 (3.3)	2 (1.7)	1 Tether replacement 1 Conversion to PSF	2 (1.7)	2 Tether removals	6 (5.0) – 2 CSF leaks 1 Keloid 3 Paresthesia
Samdani et al. [32]*	57	12.4	NR	0 (0.0)	NR	NR	5 (8.8)	5 Tether releases	0
Shankar et al. [11]	69	14.0	18 (27.0)	NR	0 (0.0)	No revision surgeries	1 (1.4)	1 Conversion to PSF	1 (1.4) – Radiculopathy
von Trueheim et al. [33]	35	13.9	4 (11.4)	NR	0 (0.0)	No revision surgeries	2 (5.7)	No revision surgeries	1 (2.9) – 1 Screw plowing
Meyers et al. [27]	49	15.0	20 (41.0)	NR	1 (2.0)	1 Conversion to PSF	NR	NR	1 (2.0)—Superior mesenteric artery syndrome (SMAS)

Table 7 (continued)

Author	Patients in cohort	Mean age (years)	Tether breakage (%)	Pulmonary complications (%)	Reoperations (%)				Other (%)
					Tether Breakage	Operation(s)	Overcorrection	Operation(s)	
Bernard et al. [26][†]	10	15.0	0 (0.0)	0 (0.0)	0 (0.0)	No tether breakages	0 (0.0)	No overcorrection	0
	10	12.6	1 (10.0)	0 (0.0)	1 (10.0)	1 Conversion to PSF	3 (30.0)	No revision surgery	0
Alanay et al. [23]	30	12.3	1 (3.2)	4 (13.3)	NR	NR	6 (20.0)	2 Tether releases 4 No revision surgery	0

NR not reported

[†] Skeletally mature and immature patients recorded in top and bottom rows, respectively

[*] Tether breakage was not analyzed in this study

[**] One case required subsequent revision of fusion for distal junctional failure

Anesthetic management and perioperative recovery

Chen et al., retrospectively compared perioperative analgesia protocols and morphine consumption at a single institution between VBT and PSF patients.[36] Thirty-five VBT patients were managed with postoperative patient-controlled epidural infusions using local anesthetic-opioid solutions for the duration the chest tube(s) were in place. Forty patients undergoing PSF had patient-controlled intravenous opioid. The total mean postoperative opioid consumption in morphine milligram equivalents was 70 (SD 76.6) for VBT and 193.4 (SD 137.2) for PSF ($p < 0.01$). These authors found that patients undergoing VBT with neuraxial analgesia require less opioid administration and are discharged earlier compared to patients undergoing PSF with standard postoperative analgesia protocols. Further study of opioid requirements and postoperative pain following VBT versus the standard spinal fusion is warranted.

In a retrospective study by Eaker et al. postoperative intravenous tranexamic acid (IV TXA) was assessed for its potential in reducing chest tube (CT) drainage and retention following VBT surgery.[35] Thirty-five VBT patients were administered 24h of post-op IV TXA (2 mg/kg/hr) and were compared to 49 patients who did not. Daily CT drainage was analyzed based on the CT location in the thoracic (T) or thoracolumbar (TL) region. In the thoracic CT IV TXA group, significantly less total CT drainage (TXA 569.4 ± 337.4 mL vs. Non-TXA 782.5 ± 338.9 mL; $p = 0.003$) and shorter CT retention (TXA 3.0 ± 1.3 vs. Non-TXA 3.9 ± 1.4 days; $p = 0.003$) were observed. Similarly, in the thoracolumbar CT IV TXA group, less total drainage (TXA 206.8 ± 152.2 mL vs. Non-TXA 395.7 ± 196.1; $p = 0.003$) and shorter CT retention (TXA 1.7 ± 1.3 vs. Non-TXA 2.7 ± 1.0 days; $p = 0.001$) were also found. Further study with 48 h of administration of TXA is being performed.

Learning curve

Baroncini et al. described the learning curve for 90 VBT cases performed by a single surgeon.[37] Overall, intubation time decreased from 439.2 ± 52.8 min for the first 20 patients to 358.4 ± 83.4 min for the last 20 patients ($p = 0.0007$). Operative time decreased from 390 ± 267.3 min for the first 20 patients to 163 ± 57.7 min for the last ($p = 0.0006$). Finally, total EBL decreased from 286.5 ± 86 ml for the first 20 patients to 188.8 ± 54.3 ml for the last 20 ($p = 0.0001$), while the mean LOS decreased from 9.3 ± 2.1 to 7.8 ± 1.6 days ($p = 0.01$). Six patients in this cohort experienced pulmonary complications within the first 6 weeks of surgery, four of whom were part of the first 25 patients. The authors conclude that there is a steep learning curve for VBT, with encouraging data to support favorable results for surgeons committed to pursuing this approach for their patients.

Mathew et al., assessed the learning curve for VBT performed with CT-guided navigation.[38] 67 patients treated by two pediatric orthopedic surgeons between 2015 and 2020 were included. EBL (52 ml reduction per year), operative time (1.3% reduction per year), anesthesia time (0.69 h reduction per year), and length of stay (0.25 days reduction per year) all significantly decreased over the 5-year period. There was no difference in correction of the major curve on first erect X-ray over time. When comparing the first 20 patients with the last 20, decreases in EBL (282 vs 116 ml), and operative time (4.8 vs. 3.3 h), anesthesia time (7.4 vs. 5.7 h), and length of stay (3.7 vs. 3.2 days), respectively, were observed. These authors similarly concluded that there is a steep learning curve that may require improved training programs and newer instrumentation.

Conclusion

Our review of the current VBT literature illustrates the potential benefits and challenges of the surgical treatment of AIS with VBT. Our review details radiographic outcomes, distinct definitions of clinical success, and the impact of skeletal maturity on outcomes, highlighting the need for further research on optimal timing for surgery. Specifically, our findings illustrate the importance of considering patient maturity in achieving successful results, and the assessment of body shape and health-related quality of life through inclinometer measurements and patient-reported outcomes. We also uncovered notable complications, including approach- and procedure-related issues pulmonary complications, tether breakage, and high rates of reoperations with varying rates of impact on clinical outcomes observed in relation to skeletal maturity. The authors hope that this review will serve as a basis for understanding the current body of literature in order to improve indications and outcomes as well as explore new approaches through further research. Ideally this could be a living document and would be updated periodically to serve as a current source of relevant information for this procedure.

Appendix

Basic science

VBT requires growth for gradual scoliosis correction via the Hueter-Volkmann Law as the basis for growth modulation in skeletally immature patients. The principle leverages the observation that skeletal growth is diminished by compression of the growth plate and increased by decreasing compression or by inducing distractive forces.[9] Seminal work on this principle in the spine was conducted by Stokes, et al. using a rat tail model. [8] Their group demonstrated vertebral wedging of individual rat tail bones after asymmetrical loading which progressed over time and leads to scoliotic deformity. In a follow-up study, their group showed the scoliosis can be corrected by reversing the applied load.[22]

A number of larger animal studies were subsequently endeavored and have shown the feasibility of using non-fusion tether-based applications in skeletally immature spines to both create scoliosis and correct it while permitting at least some longitudinal growth. Disk integrity has also been shown to be maintained. Newton et al. conducted two in vivo studies in bovine[23] and porcine models[24] to evaluate the effects of intraoperative tensioning of flexible spinal tethers on spinal growth and motion using stainless steel cables. In the bovine model, his team first performed right-sided tethers of four thoracic vertebrae and four screws without tether as a sham operation on the contralateral side. Tethering caused scoliosis (11.6° ± 4.8°) and disk wedging (6.8° ± 1.6°) with decreased vertebral height. In the porcine model, pre-tensioning induced scoliosis and apical disk (T9–T10) wedging, but after 12 months, no radiographic differences were observed between groups, suggesting growth modulation is possible in untensioned states. Furthermore, spinal motion and disk health were not negatively affected after tethering. Histology showed normal disks and intact growth cartilage along with no foreign bodies or microabscesses on lymph tissue analysis.

Braun et al. created an immature goat model to predict scoliosis progression by analyzing the percentage of vertebral body wedging, specifically in the area of maximal deformity.[25] They induced scoliosis in 15 goats and observed them for 12 weeks. Seven goats developed progressive curves (mean: + 10.1°), while eight goats did not show progression (mean: − 1.6°). Their results indicated that a higher percentage of vertebral body wedging was associated with progressive curves, suggesting its potential as an indicator for risk of curve progression in idiopathic scoliosis.

Patel et al. created another porcine scoliosis model with curvature of 50 degrees achieved to potentially evaluate VBT.[26] Moal et al. used this model to explore the non-fusion correction of tethering.[27] The pigs were divided into three groups: the Scoliosis Model (SM) group served as the control and was euthanized after the scoliotic curve reached a specific angle; the Tether Release (TR) group had the inducing spinal tether removed and was observed for ongoing growth modulation; and the Anterior Correction (AC) group had the tether removed and received an anterior corrective tethering technique. The AC group demonstrated favorable realignment in all three planes and correction of vertebral wedging, indicating potential advantages over fusion-based approaches in preserving spinal growth and mobility. They found tethering offers advantages over fusion-based methods, preserving spinal growth and mobility.

Biomechanics

Various studies highlight the importance of instrumentation parameters in VBT such as tether tensioning, the amount of stress applied by the tether on the instrumented spine, screw positioning, the number of tethers used, and the positioning of the patient.

Lalande et al. explored tether tensions and pressures transmitted onto the vertebral end plates of a tether applying cyclical loads in a porcine model.[28] In a previous experiment on rat and mouse tail vertebrae by Valteau et al. axial cyclical compressions allowed for similar growth modulation as for standard statically loaded tethers, while providing better preservation of the intervertebral disks and soft tissues of the instrumented intervertebral segments. Reductions in growth plate thickness and the number of proliferative chondrocytes per column in static conditions compared to cyclical loading, suggesting differential response of growth plates of between the two loading mechanisms.[29] Lalande et al. then developed a cyclical VBT prototype with a motor box that applied automated cyclical tensioning. Five different tensions were tested, revealing pressure exerted on the end plate was linearly correlated to the mean tether tension ($r^2 = 0.86$). The results of these studies suggest some benefit of a cyclically loading VBT concept though further study is needed.

Cobetto et al. investigated the use of an anterior vertebral body growth modulation (AVBGM) in correcting pediatric scoliotic deformities.[30] The device aims to modify the compression distribution on vertebral body growth plates by applying compressive forces on the convex side of the scoliotic curve. The authors used patient-specific finite element models to simulate the effects of different instrumentation parameters and patient positions on the 3D corrective effects of AVBGM. They found that AVBGM can provide significant correction in the coronal and sagittal planes, but not in the transverse plane. The results offer valuable insights to improve the biomechanical knowledge and design of AVBGM and could help personalize the surgery to improve treatment outcomes.

Nicolini et al. investigated the impact of VBT on the range of motion (ROM) within the thoracolumbar spine.[31] They tested different surgical reconstruction groups, including the native spine, one tether, two tethers, and a hybrid construction. Compared to the native spine, VBT with one or two tethers led to a slight reduction (less than 9.7%) in global ROM during flexion and extension, and up to 13.5% reduction in right axial rotation. In lateral bending, VBT significantly reduced global ROM by around 25–45%. The hybrid technique showed the least impact on global ROM in flexion–extension and axial rotation, with reductions of less than 10.5% and 10–14%, respectively. The results suggested that the double tether or hybrid surgery may still preserve global motion in flexion–extension and axial rotation.

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Declarations

Conflict of interest Dr. Lonner reports personal fees, royalty fees, and research grant support from ZimVie Spine for The Tether implant. Dr. Lonner also reports personal fees, non-financial support, and other from Depuy Synthes; personal fees and non-financial support from OrthoPediatrics; other from Paradigm Spine; non-financial support and other from Spine Search; and other from Setting Scoliosis Straight Foundation, outside the submitted work. The remaining authors have no disclosures to report.

Ethical approval This work did not require approval by the Institutional Review Board at Mount Sinai Hospital as it is a literature review. Made substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data: HA, RR, YA, AW, BL. Drafted the work or revised it critically for important intellectual content: HA, RR, YA, AW, BL. Approved the version to be published: HA, RR, YA, AW, BL. Agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved: HA, RR, YA, AW, BL.

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