RESEARCH ARTICLE

Treatment of Patients with Scoliosis Using a Unique Anterior Scoliosis Correction Technique

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Abstract

Treatment for adolescent idiopathic scoliosis (AIS) is dependent upon multiple factors, including curve type and magnitude, curve progression, skeletal maturity, and clinical trunk deformity. While fusion is effective at achieving curve correction, it is associated with disadvantages including prominent implants beneath the skin, back muscle scarring and atrophy, decreased spine range of motion, and decreased functional spinal mobility. Additional concerns include the potential for longer term development of premature adjacent level disc and facet joint degeneration above and below the fusion. Due to these issues with spinal fusion, surgeons have explored alternative surgical approaches to correct spinal deformity and halt curve progression using either growth modulation or remodeling of the spine while preserving motion. This paper provides an overview of a non-fusion scoliosis correction technique called Anterior Scoliosis Correction (ASC).

1. Introduction

Treatment for adolescent idiopathic scoliosis (AIS) is dependent upon multiple factors, including curve type and magnitude, curve progression, skeletal maturity, cosmetic deformity, and limitations in cardiopulmonary function.[1] The most common indication for surgical intervention is curve progression. The current standard of care is to perform a posterior spinal fusion (PSF) of the involved vertebral body segments. While fusion is effective in achieving curve correction, it is associated with many problems, including development of adjacent level disc degeneration in the lumbar spine, risk of reoperation for pain, decreased range of motion, and decreased functional spinal mobility.[2-4] Additional concerns include the potential for longer term development of increased back pain and lower extremity joint problems.[2,5-7] Due to these issues with spinal fusion, surgeons have explored alternative surgical approaches to correct spinal deformity and halt curve progression using either growth modulation or remodeling of the spine while preserving motion.[8-10]

This paper provides an overview of two non-fusion scoliosis anterior correction techniques, vertebral body tethering (VBT), and Anterior Scoliosis Correction (ASC). ASC is the multi-year, multi-generational advancement of VBT using the same screws and cords as VBT but is not dependent on growth modulation. ASC can be performed on both immature and mature patients, allows for more curve correction through better derotation at surgery, and can create more kyphosis.[11] ASC is based on the principle of detethering, not tethering, the scoliotic spine.

2. Description of Non-Fusion Correction Techniques: Vertebral Body Tethering and Anterior Scoliosis Correction

2.1. *Vertebral Body Tethering (VBT)*

VBT has emerged as a new, preferred technique for instrumented spinal growth modulation.[12] VBT involves placement of anterior vertebral body screws on the convex side of a scoliotic curve through an open or thoracoscopic technique.[10] A flexible cord is then inserted into the screws and sequentially tensioned to achieve partial curve correction by acting as an impediment to convex spine growth while allowing for continued growth on the concave side of the curve.[12]

Current indications for VBT include skeletally immature patients (Risser 0–2) with idiopathic thoracic major scoliosis of 35 to 65° without structural compensatory curves.[12-17]

Patients with thoracolumbar or lumbar curves, those with large, stiff thoracic curves, or patients who are skeletally maturing or mature (Sanders hand score > 4) are generally not considered good candidates for VBT due to its limited corrective ability below 30° degrees and virtually no derotational correction.

2.2. *Anterior Scoliosis Correction (ASC)*

Given that patients who are skeletally maturing or mature, have thoracolumbar or lumbar curves, or have stiff thoracic curves are generally not considered candidates for VBT, we advanced the technique, adopting the primary principle of detethering the scoliotic curve and effecting significant derotation in correction that allows inclusion of more patient types. Anterior scoliosis correction (ASC) utilizes a muscle-sparing thoracotomy approach to thoracic, thoracolumbar, or lumbar curves, incorporating the same screws and cords as VBT but adding anterior releasing techniques of the anterior longitudinal ligament and thoracic disc annulus as needed. In addition to allowing for significant curve correction through unrestricted derotation at surgery, ASC can restore kyphosis, as needed, and spare segmental vessels.[11]

Indications for ASC in skeletally immature, maturing, and mature patients have broadened compared to those previously described for VBT to include moderate but also large curves (> 65°). Also importantly, there is not a limit due to flexibility, as VBT only accommodates curves that bend to less than 30° on bending films.[10] Key differences between ASC and VBT are summarized in **Table 1**.

Table 1. Characteristics of Vertebral Body Tethering (VBT) versus Anterior Scoliosis Correction (ASC)

	Vertebral Body Tethering	**Anterior Scoliosis Correction**
Curves 30-65°	Yes	Yes
Curves > 65°	No	Yes
Flexible curves (< 30°)	Yes	Yes
Stiff curves (bend not less than 30°)	No	Yes
Growing spine (Sanders ≤ 4)	Yes	Yes
Maturing spine (Sanders 5-7)	No	Yes
Mature curves (Sanders 8)	No	Yes
Correct thoracic hypokyphosis	No	Yes
Effective derotation	No	Yes

3. Surgical Technique of Anterior Scoliosis Correction (ASC)

All reported cases were performed by the lead surgeon, MDA. ASC is performed through a single incision, anterior muscle-sparing thoracotomy to thoracic, thoracolumbar, and/or lumbar curves performed in the lateral decubitus position with the convexity of the curve oriented in the superior or "up" position. The average length of the incision is 10-12 cm. There may need to be a port incision above for access to T5-T6 or one below for long thoracic curves that extend down to L2 or L3. Additional port incisions are not typically needed for primary thoracolumbar or lumbar curves, but additional subfascial ports are often utilized. Fluoroscopic views are taken prior to the incision to determine the location of the vertebrae to be instrumented and mark the location for the incision. Patients undergo single lung ventilation of the opposite lung to provide additional visualization into the chest cavity and to allow for placement of instrumentation. The parietal pleura is carefully dissected off the lateral aspect of the vertebral body anterior to the rib heads and is reflected anteriorly with sparing of many of the segmental vessels.

After the appropriate spinal levels requiring instrumentation are identified and exposed, and with the assistance of fluoroscopic imaging, 1 or 2 three-prong staples are inserted into each vertebra anterior to the rib head. A threaded awl is then utilized to create the screw trajectory through the vertebral body and to ascertain screw length. Use of the PediGuard (SpineGuard, Paris, France) reduces the need for fluoroscopy while identifying bicortical purchase with minimal excursion into the contralateral chest cavity to decrease the potential for vascular or lung injury. Screw length is confirmed via measurements on the SpineGuard threaded tap as well as reconfirmed with a ball tip probe. All screws come manufactured with a hydroxyapatite coating and are placed in this manner with their final positioning confirmed with AP and lateral views using fluoroscopic imaging.

Anterior longitudinal ligament and annular disc releases are considered for most curves. We use releases routinely to help correct curves that are determined to be hypokyphotic, significantly rotated, and/or unflexible on coronal view to < 20° on intraoperative radiographs. These releasing procedures allow for additional segmental derotation to correct the scoliosis and/or create kyphosis.[11] Of note, these releasing procedures are performed in the thoracic and upper lumbar spine only and are not a fusion, as the cartilaginous end plates are preserved. The release of the anterior longitudinal ligament and constricted disc annulus allows additional segmental derotation to obtain correction by “detethering” the stiff and rotated scoliotic spine in the sagittal, axial, and coronal planes.[11] The ligament and annulus then heals with the spine in a corrected position and holds the correction obtained at surgery while additional bone remodeling may occur.

The cord, composed of polyethylene terephthalate (PET), is then introduced from proximal to distal. Each vertebral segment is corrected with the use of translation first. The most important correction is applying translation and derotation of the distal vertebral body segment using the proximal vertebral body segments as counter torque. This is facilitated by having a small open thoracotomy to allow for complete rotation of the vertebral segment. Once translated and derotated, compression of the 2 vertebrae through tensioning is applied. When the cord is tensioned, the set screws are tightened to maintain the correction. This technique is repeated for each instrumented level. In the majority of current cases, we now use a 2-screw and 2-cord construct where the posterior cord is tensioned first and the anterior cord second. This 2-screw and 2-cord construct helps both to achieve additional derotation and to maintain the rotation correction. Preliminary unpublished biomechanical pilot work shows better stabilization of correction but no loss of mobility compared to single screw/single cord constructs.

Maximum coronal, axial and sagittal correction is obtained in skeletally maturing (Sanders 5 to 7) and mature (Sanders 8) patients in the operating room as there is no significant growth modulation after Sanders 4, whereas in skeletally immature patients (Sanders $\leq$ 4) one leaves residual curves of 10 to 15° to allow for growth modulation.

After final radiographs are taken, the parietal pleura is partially repaired, the hemithorax is irrigated, a chest tube is placed, the lung is reinflated, and the wound is closed in a multilayered fashion.

For patients with double curves, after completion of the thoracic curve, the patient is repositioned to the opposite lateral decubitus position and an identical procedure is performed with additional fixation in transition vertebrae of the two curves (e.g., typically T11 or T12). Segmental vessels in the thoracic spine are preserved for as many vertebrae as possible.

4. Results of ASC in Immature Patients (Sanders ≤ 4) with Growth Modulation

We performed a retrospective analysis to examine outcomes of a cohort of skeletally immature patients treated with ASC. Inclusion criteria comprised a diagnosis of AIS and at least one operative curve (thoracic or lumbar) with a minimum major coronal curve angle of 35° and maximum of 70°, skeletally immature at the time of surgery (Risser 0 or 1, Sanders ≤ 4), and minimum 2-year follow-up.

Twenty-eight patients met the inclusion criteria. Mean follow-up was 32 months and average age at surgery was 12.6 years. Preoperative curves for the instrumented thoracic and lumbar curves were 55.4 ± 10.2° (range 35 to 70°) and 49.5 ± 12.7° (range 36 to 70°), respectively. The final average postoperative thoracic curve was 16° ± 10.6° (range -3 to 34°) and the final average lumbar curve was 13.9 ± 8.9° (range -5 to 28°). Percent correction at > 2 years was 71% for thoracic curves and 72% for lumbar curves. Clinical success (curves ≤ 30°) was achieved in 26/28 patients (93%) and 37/39 curves (95%).

Estimated three-dimensional (3D) kyphosis values were calculated utilizing the two-dimensional (2D) measurements and a validated formula to predict 3D kyphosis as described by Parvaresh et al.[13] The formula to estimate 3D kyphosis is the following: 3D T5-T12 kyphosis = 18.1 + (0.81*2D T5-T12 kyphosis) – (0.54*2D thoracic major coronal curve) degrees. 3D kyphosis (T5-T12) corrected from preoperative average of 11.8° to postoperative average of 28°.

There were 3/28 (11%) anticipated lengthening procedures and 1/28 (4%) unanticipated revision surgery. Anticipated revision surgery included possible overcorrection of scoliosis secondary to excessive growth modulation requiring cord tension adjustment **(Fig. 1A-G)**.

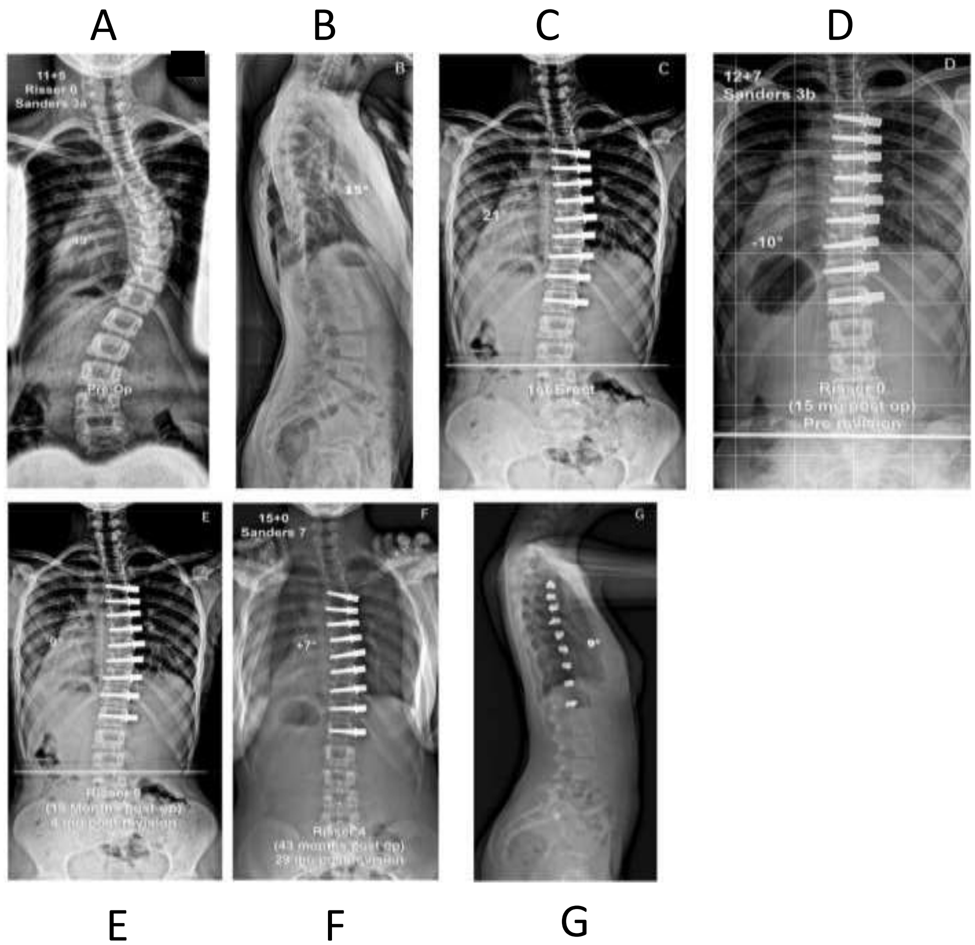

Fig 1A-G. Example of anticipated revision for overcorrection in 11.5-year-old girl (Risser 0, Sanders 3A). (A) Presenting coronal x-ray with worsening trunk shift. (B) Pre-op lateral x-ray. (C) First erect x-ray following T5-L1 ASC. (D) Follow-up PA radiographs at 15 months postoperatively show overcorrection of 10°. (E) 4-month post-revision. A longer cord was used to address overcorrection. (F) 29 months post revision surgery (43 months post index procedure). The patient is now Risser 4, Sanders 7. Correction is maintained. (G) Post-op lateral x-ray at 43 months post index procedure. We did not do disc releases on this patient, and therefore there was no correction of the hypokyphosis. This case and others have led to us doing routine disc releases on these immature patients to help obtain normal kyphosis.

5. Results of ASC in Maturing (Sanders 5 to 7) and Mature Patients (Sanders 8) with Remodeling

We performed a retrospective analysis to examine outcomes of a cohort of skeletally mature patients treated with ASC. Inclusion criteria included patients ≤ 21 years of age with a diagnosis of AIS and at least one operative curve measuring ≥ 35°. All patients had to be classified as skeletally maturing (Sander 5-7) or mature (Sanders 8) at the time of surgery and have minimum 2-year follow-up.

Forty-nine patients with 82 curves met the inclusion criteria and were evaluated. Mean preoperative curves for the instrumented thoracic (49) and lumbar (33) curves were 55 ± 11° (range 30 to 84°) and 51 ± 10° (range

37 to 78°), respectively. Mean follow-up was 30.3 ± 7.1 (range 24-50) months.

The most superior thoracic level to be instrumented was T4 and the most inferior instrumented level was L4. Disc releases were performed in 35/49 patients (71%) and only in the thoracic curves.

In patients with instrumented thoracic curves, the average preoperative curve of 55° (range 35 to 84°) was corrected to an average postoperative major coronal curve angle of 19° (range 5 to 37°), for an average 65.5% correction **(Fig. 2)**.

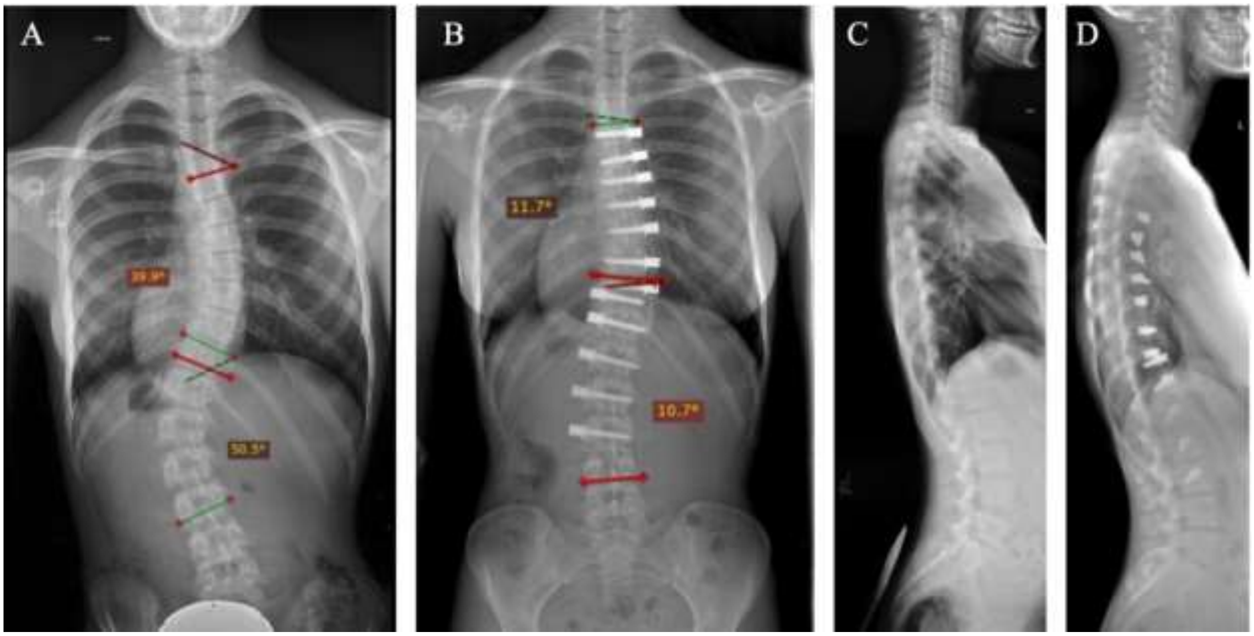

Fig. 2. (A) Preoperative and (B) 50-month PA radiographs of 13-year-old girl (Risser 3, Sanders 5) with AIS who underwent ASC with no disc releases. Patient demonstrated preoperative curves of 40° (thoracic) and 51° (lumbar). Curves were 12° (thoracic) and 11° (lumbar) at 50-month follow-up. 3D kyphosis (C & D) improved from 4° preoperatively to 21° post operatevely. There was suspected cord breakage at 3 levels (T9/10, T10/11, and L2/3) which occurred by 2-year follow-up with no further loss of correction.

In patients with instrumented lumbar curves, the average preoperative curve of 51° (range 37 to 78°) was corrected to an average postoperative major coronal curve angle of 17° (range 5 to 47°), for an average 66.7% correction. Of note, 1 patient had a Lenke 6 curve where the lumbar curve met the inclusion criteria, and the 30° thoracic curve was instrumented to balance the shoulders. Preoperative and postoperative kyphosis measurements for all instrumented curves are shown in **Table 2**.

Table 2. Kyphosis Measurements

3D kyphosis, mean ± SD (range), degrees	Preoperative	Postoperative	P-value
All patients (n=46*)	2.1° ± 16.1° (-22.4° to 35.6°)	33.6° ± 8.8° (13.8° to 53.2°)	<0.001

*n=46 because 1 lateral film was unavailable for review in 3 patients

There were no revisions for cord breakage and only 1 recommended revision for a patient with both instrumented thoracic and lumbar curves. At 30 months follow-up, this patient demonstrated successful thoracic correction from 43 to 26°, but the lumbar correction was lost due to lumbar cord breakage (splaying at L1/2 and L2/3), from 63° preoperatively to 10° immediately postoperatively to 47° at 30 months. Revision was recommended but the patient opted not to undergo revision.

Clinical success (final curve ≤ 30°) at > 2-year follow-up was achieved in 47/49 (96%) of all thoracic curves (range 5°–37°), and in 31/33 (94%) of all lumbar curves (5 to 47°). The 2 thoracic curve failures measured 31° and 37° at 2-year follow-up. The 2 lumbar curve failures measured 32° and 47° at 2-year follow-up.

5.1. Adverse Event: There was 1 (2.0%) neuromonitoring event in the mature patient cohort. The patient was a 13-year-old girl with a Lenke 3C curve pattern (63° thoracic, 52° lumbar) undergoing a bilateral ASC. The thoracic curve was corrected without complication, but loss of neuromonitoring motor signal occurred during correction of the lumbar spine. Intraoperatively, this patient demonstrated loss of motor signals for unknown reasons but had normal motor movement with a wake-up test. The lumbar correction was stopped and was subsequently completed 1 week later without issue. The patient had normal motor signals during the completion surgery. This patient reported anterior thigh numbness and skin hypersensitivity for approximately 1 year postoperatively. The patient's thoracic and lumbar curve corrections were considered successful at most recent follow-up (29 months).

There were 6 (12.2%) intraoperative and postoperative medical complications. There were 2 major complications: 1 chylothorax and 1 intraoperative tear of the inferior vena cava (IVC). The chylothorax was initially drained via a chest tube but was ultimately treated with embolization on postoperative day 12 with resolution. The IVC tear was repaired intraoperatively, and the surgery was completed uneventfully without transfusion, as estimated blood loss for the case remained low at 500ml. Four of these complications were considered minor: 3 cases of superior mesenteric artery (SMA) syndrome, and 1 delayed hemothorax.

6. Results of ASC in Early Onset Scoliosis (i.e., < 10 years)

We have performed ASC on 10 patients with early onset scoliosis (EOS, age < 10 years, Sanders ≤ 2, Risser 0, open triradiate cartilage). Mean follow-up was 12 months. Average age at surgery was 8.6 years. The average preoperative thoracic curve was 85.9° (range 70 to 97°). The most recent postoperative curve was average 36° (range

27 to 52°) for an average 55% correction (range 41 to 74%).

These preliminary results suggest that for very young patients with severe curves, ASC may be a good alternative to magnetically controlled growing rods and ultimate spinal fusion.

7. Progressive Neuromuscular Scoliosis Secondary to Spinal Cord Injury

98% of skeletally immature patients with spinal cord injury (SCI) suffer from progressive neuromuscular scoliosis (NMS). Additionally, many children with myelomeningocele and paraplegia have severe progressive scoliosis. Operative treatment has typically been limited to posterior spinal fusion (PSF), typically of the entire spine to the pelvis. However, ASC may be less invasive and able to preserve more flexibility (and thus more function for the patient) as well as spinal growth. We reported a case of ASC to treat progressive NMS in an 11-year-old girl with T10 level (ASIA A) paraplegia and a progressive 60° NMS of the lumbar spine.[18] She had an ASC from T11-L5 without fusion. Over 24 months, the curve growth-modulated to a residual of 12° with continued modulation to 7° at 3-year follow-up (skeletal maturity).

8. Lumbosacral Spondylolisthesis in an Immature Patient with Marfan Syndrome

We reported on a 12-year-old girl with Marfan syndrome, spondylolisthesis, and severe progressive scoliosis who underwent a two-stage procedure to achieve correction.[19] Muscle sparing posterior far lateral interbody fusion (FLIF) of the spondylolisthesis from L4-S1 was initially performed, followed 1 week later by ASC from right T4-T11 and left T11-L3. Follow-up from the index procedures for the spondylolisthesis and scoliosis was 35 months. No significant complications occurred in the perioperative and postoperative follow-up periods. At 13 months follow-up, the double-major scoliosis showed continued curve correction via growth modulation and overcorrection of the lumbar curve to -13°. A revision lengthening procedure of the anterior cord from T11-L3 was performed. An asymptomatic elevated hemidiaphragm was discovered at 6 weeks post-op, which was believed to be secondary to retraction neuropraxia; it subsequently improved. At 21 months post-lengthening and 35 months post index procedure, she is skeletally mature, and the curves have maintained correction in both the coronal and sagittal planes without any further complications.

9. Congenital Scoliosis

A 13-year-old girl with a semi-segmented T9 level hemivertebra had developed a progressive 50º congenital scoliosis with significant trunk shift. She was a Risser 0, Sanders 6 at presentation and Risser 2, Sanders 6 at the time of surgery. She had an ASC from T7-L1 without fusion.

The patient now has 4 years of follow-up and is currently Risser 4+ and Sanders 8. No significant complications occurred in the perioperative and postoperative follow-up periods. Because she was classified Sanders 6 at the time of surgery, we obtained maximal correction, and her initial coronal postoperative curve was 11°. This has remained completely stable, and her most recent radiographs at 4 years post-op measured 11º in the instrumented thoracic curve, indicating 78% correction. Her sagittal profile also remained stable, with 3D thoracic kyphosis measurements of 18° preoperatively, 27° at first erect, and 27° at 4 years.

10. ASC in an Adult

A 51-year-old woman with a 38° curve as a late teen presented with progressive scoliosis measuring 70° at evaluation. Over time, she had developed significant back pain associated with curve progression and increasing right trunk shift, which she managed with core strengthening. The patient requested curve stabilization without spinal fusion in order to maintain her current level of physical activity, particularly yoga, and decrease her back pain and trunk shift.

The patient subsequently underwent ASC from T5-L1. No significant complications occurred in the perioperative and postoperative follow-up periods. The initial postoperative coronal curve of 31° has remained stable at 5-year follow-up. The patient's sagittal profile (from T5-T12) also corrected and remained stable, with 3D thoracic kyphosis measurements of 6° preoperatively, 25° at first erect, and 25° at 5-year follow-up. She returned to work and full activity 6 weeks after surgery with no long-term complications.

11. Conclusion

Due to issues with spinal fusion, surgeons have explored alternative surgical approaches to correct spinal deformity and halt curve progression using either growth modulation or remodeling of the spine while preserving motion. We report a new correction technique called Anterior Scoliosis Correction (ASC). ASC is our multi-year, multi-generational advancement of VBT, using the same screws and cords as VBT but based on the principle of detethering the scoliotic spine, and is not dependent on growth modulation. ASC can be performed on both immature and mature patients, allowing for more curve correction through significant derotation at surgery, and can restore normal kyphosis. ASC can be used for patients with both idiopathic scoliosis and with other diagnoses with good predictable clinical success in > 90% of patients.

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