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RESEARCH ARTICLE

# Double Screw-Line Technique of Anterior Scoliosis Correction with Thoracic Disc Releases for Thoracic Curves > 65 Degrees: Surgical Techniques and Outcomes

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## ABSTRACT

Anterior Scoliosis Correction (ASC) is the proprietary technique of the authors and is an anterior spinal "de-tethering" technique using multiple flexible rod-cords and multiple screw constructs. It is performed through a modified anterior fusion approach that is a muscle-sparing mini-thoracotomy. ASC is the multi-year (since 2013), multi-generational modification of the original anterior vertebral body tethering procedure but includes preservation of the segmental arteries and incorporates multilevel releasing techniques of the contracted anterior longitudinal ligament and annular disc complex. Because of this, ASC, unlike vertebral body tethering, has been shown to derotate the hypokyphotic scoliotic spine effectively towards a more normal thoracic kyphosis and is not restricted to small curves or pediatric patients with growth remaining as is vertebral body tethering.

We retrospectively reviewed all 309 ASC procedures performed between September 2017 and August 2020, and 26 patients met the inclusion criteria (adolescent idiopathic scoliosis and at least a thoracic operative curve with severe coronal curve angles between 66° and 90°, double screw and rod-cord construct, and minimum 2-year follow-up). The results of ASC on severe curves showed an average curve correction of 78.4% in thoracic and 71.2% in lumbar curves in the instrumented curves. Anterior longitudinal ligament and annular disc complex releases were performed on all patients having thoracic curves to help obtain adequate correction. An average of 4.1 discs per patient were released, all in the thoracic region. Clinical success with residual curves ≤ 35° was 96% (25/26 curves) in all patients and 92.3% in patients with curves ≤ 30° (24/26 curves). Three-dimensional (3D) thoracic kyphosis corrected an average of 39° from preoperative hypokyphosis of -4° to 35° postoperatively. There were no revisions performed in this group of patients.

In conclusion, Anterior Scoliosis Correction has potential expanded indications and increased ability to correct severe curves (> 65°) in patients with adolescent idiopathic scoliosis as compared to vertebral body tethering.

**Keywords:** Anterior Scoliosis Correction; Adolescent Idiopathic Scoliosis; Anterior Vertebral Body Tethering; Kyphosis Restoration; Severe Curve

## 1. INTRODUCTION

Adolescent idiopathic scoliosis (AIS) is a complex three-dimensional deformity that often requires surgical intervention.[1] Posterior spinal fusion (PSF) is recommended for patients whose curves continue to progress or reach a coronal curve angle of 50°.[2] This is done to prevent further progression and future cardiopulmonary deterioration, back pain, lower extremity problems, and cosmetic concerns.[3-7] The current standard of care is to correct the deformity with a PSF of the involved vertebral body segments utilizing a combination of pedicle screws and inflexible metal rods.[2, 8] Posterior spinal fusion allows viable long-term outcomes but is linked with diminished spinal flexibility and, hence, decreased functional outcomes.[9,10] Furthermore, the long-term effects of these extended posterior fusion constructs for children with AIS can result in increased back pain, adding-on phenomenon, pseudarthrosis, and adjacent segment disease.[6]

Anterior vertebral body tethering (VBT) was introduced over a decade ago as an anterior fusion approach combined with a flexible cord/screw construct to correct scoliotic curves. Because of technical limitations, its use is restricted to smaller curves in growing individuals only. It has been shown that tensioned tether constructs allow greater spinal mobility than the classic rigid metal rod constructs.[3, 6] Thoracoscopic approaches are usually employed and have been shown to be safe in various studies of immature patients with AIS.[6, 11, 12] Additionally, this method of spine growth modulation, utilizing the Hueter-Volkmann principle, potentially provides ongoing correction of spine deformities without arthrodesis in patients who are skeletally immature.[4,13-15] Currently, indications for VBT include skeletally immature patients with thoracic curves ranging from 35° to 65° and which demonstrate flexibility to < 30° on bending films.[11, 14]

Anterior Scoliosis Correction (ASC), developed by authors M.D.A., L.A.C., and R.R.B., is a spinal "de-tethering" technique using multiple flexible rods-cords and multiple screw constructs designed to address the shortcomings of VBT. These include limited curve correction, smaller curve size, lack of curve derotation, and high recurrence rates, and it is limited to patients with remaining growth only. Anterior Scoliosis Correction is the authors' multi-year (since 2013), multi-generational modification of the original anterior VBT technique but includes preservation of the segmental arteries and multilevel release of the contracted anterior longitudinal ligament and annular disc complex.[16-18] It is performed through a modified anterior approach using muscle-sparing mini-thoracotomy, and ASC, unlike VBT, has been shown to derotate the hypokyphotic, scoliotic spine effectively towards a more normal thoracic kyphosis.[16-18] Vertebral body tethering is unable to derotate the spine towards normality. Because of effective derotation, ASC can be used to treat most thoracic, thoracolumbar, and lumbar curves in both immature and mature patients including those with stiff and severe curves with an age range from approximately 5 to 50 years. This paper reviews the outcomes of a cohort of skeletally immature and mature AIS patients with severe curves (measuring ≥ 66° and ≤ 90°) who underwent ASC using a double screw rod-cord construct.

## 2. METHODS

### *2.1 Inclusion Criteria*

After obtaining Institutional Review Board approval from our surgical facilities, we conducted a retrospective review of all Anterior Scoliosis Correction procedures performed between September 2017 and August 2020. Inclusion criteria comprised a diagnosis of AIS and at least one operative curve with a minimum major coronal thoracic curve angle of 66° and maximum 90° and a fulcrum bend flexibility ≥ 50%. If a patient possessed an additional secondary curve that was deemed to be structural and it was instrumented, they were included within our analysis. Also, patients had to have undergone the authors' proprietary double screw-line construct of ASC at the time of surgery with a minimum 2-year follow-up. Patients were considered to have a true double screw-line construct if their correction was obtained via a primary double screw-line construct with < 3 single screws in the thoracic or < 2 single screws in the lumbar. Patients were considered to have a mixed screw construct if their correction was obtained with a mixed double and single screw construct with ≥ 3 single screws in the thoracic region or ≥ 2 single screws in the lumbar region. They were classified as having a single screw construct if only single screws were used in the thoracic or lumbar regions to obtain correction. Patients were excluded if their correction was not obtained via a true double screw-line construct.

### *2.2. Surgical Techniques*

All reported cases were performed by the primary surgeon M.D.A. Anterior Scoliosis Correction is performed in the lateral decubitus position with the convexity of the curve oriented in the superior or "up" position. A single incision is made with anterior muscle-sparing thoracotomy to access thoracic, thoracolumbar, and/or lumbar curves. The average length of the incision is 10-12 cm. A port incision above may be needed for access to T5-T6 or one below for long thoracic curves that extend down to L2 or L3, either incisional or most often subfascial. Additional port incisions are not typically needed for primary thoracolumbar or lumbar curves, but additional subfascial ports are often used. 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.

The appropriate spinal levels are identified and exposed for instrumentation with the assistance of fluoroscopic imaging. The majority of segmental vessels are preserved by dissecting them for mobility and shifting them cephalad or caudal so that 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 as the device differentiates between the conductivity of cancellous bone, cortical bone, and soft tissue. This allows bicortical purchase to be identified with minimal excursion into the contralateral chest cavity and decreases the risk of vascular or lung injury. Screw length is confirmed via measurements on the PediGuard threaded tap as well as reconfirmed with a ball tip probe. All screws have a hydroxyapatite coating and are placed in this manner with their final bicortical positioning confirmed with posteroanterior (PA) and lateral views using fluoroscopic imaging.

Anterior longitudinal ligament and annular disc releases are performed for all curves. Releases are routinely used to assist in curve correction and for maintenance of curve correction as the complex heals and stabilizes in the corrected position. These releases are performed in both the thoracic and lumbar spine. Of note, the releases are not bone to bone as is done in metal rod fusion surgery which destroys the disc space. In ASC the cartilaginous end plates are preserved. The release of the contracted anterior longitudinal ligament and constricted annular disc complex allows significant segmental release and derotation during correction by "de-tethering" the stiff and rotated scoliotic spine in the sagittal, axial, and coronal planes.[2] The anterior longitudinal ligament and annular disc complex then heals with the spine in a corrected position, which stabilizes the correction obtained at surgery while additional bone remodeling may occur as well.

The cord, composed of polyethylene terephthalate (PET), is then introduced from proximal to distal. Each vertebral segment is corrected first with the use of translation. The most important correction is applying translation and derotation of the next 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 derotation of the vertebral segment. Once translated and derotated, the 2 vertebrae are compressed through tensioning. When the cord is tensioned, the set screws are tightened to maintain the correction. This technique is repeated for each instrumented level. 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 maintain the rotation correction. Preliminary unpublished biomechanical pilot work shows better stabilization of correction compared to single screw cord constructs but notably no significant loss of mobility.

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.

In skeletally immature patients (Sanders ≤ 4), one may leave 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 on the lumbar curve. In the transition vertebra of the two curves (e.g., typically T11 or T12) segmental vessels are preserved as much as possible as there will be screws implanted from both sides of the vertebra.

*2.3. Data Collection*

Radiographic variables analyzed included perioperative fulcrum-bending angles, coronal curve angles of proximal thoracic, thoracic, and lumbar curves, sagittal curve angles of T5-T12, lordosis, Sanders stage, and Risser sign. Measurements were made by two to three of the physician authors to confirm accuracy. Radiographic evaluation included: preoperative posteroanterior (PA) and lateral films, preoperative bending films, left hand radiograph, and first erect postoperative films. Postoperative PA and sagittal radiographs (with a negative value applied to overcorrected curves) were measured at 1 year, 2 years, and most recent. Additionally, the number of levels instrumented, the performance of anterior releases, and intraoperative and postoperative complications (including neuromonitoring changes) were recorded.

Spinal flexibility was calculated using the following formula for each curve: (Preoperative coronal curve – fulcrum bending coronal curve) / preoperative coronal curve) x 100 = % flexibility. Two-dimensional (2D) thoracic kyphosis measurements were calculated using sagittal radiographs from preoperative imaging as well as most recent postoperative follow-up imaging. Estimated three-dimensional (3D) kyphosis values were calculated utilizing the 2D measurements and a validated formula to predict 3D kyphosis as described by Parvaresh et al.[19] 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 coronal curve) degrees (°)

This formula has an average model error between predicted and actual measurements of +/- 7.0°.

Cord breakage, first described by Newton et al.,[12] was determined to have occurred if there was an increase of > 5° of angulation over time between any two adjacent screws (splaying) on comparative radiographs.

Revision surgeries were categorized as anticipated or unanticipated. Anticipated revision surgery included possible overcorrection of scoliosis secondary to excessive growth modulation requiring adjustment of cord tension. Additionally, in our practice, staged corrections are sometimes planned for very large, stiff curves.

Unanticipated revision surgery was defined as surgery in those patients who experienced cord splaying with coincident curve progression or those with progressive scoliosis (without cord splaying) who would qualify for either revision ASC and/or PSF.

ASC was considered successful if at the time of latest follow-up the curve magnitude was ≤ 30° and the patient experienced no occurrence of an unanticipated revision ASC procedure or a posterior spinal fusion. The value of ≤ 30° was chosen as a demarcation for success because the 50-year natural history studies conducted by Weinstein et al.[20] showed low risk of progression of curves at maturity if they measured < 30°. Additionally, this value falls below any indication for spinal fusion.[11, 12] Furthermore, there is precedence for this technique in scoliosis correction procedures as modeled after a recent study by Miyanji et al.[11] Many recent VBT studies are using ≤ 35° as the cutoff for success.

## 3. RESULTS

### *3.1. Patient Demographics*

During the study period between September 2017 and August 2020, 309 patients underwent Anterior Scoliosis Correction. Of these, 30 met the criteria including a diagnosis of AIS, thoracic coronal curve angle of 66-90°, fulcrum bend flexibility > 50%, and primary double screw-line construct of the thoracic curve. Of those, 26/30 (87%) had 2-year radiographic follow-up. Follow-up was limited due to the global distribution of patients and the COVID-19 pandemic.

Of the 26 patients who met all the inclusion criteria, including ≥ 2-year follow-up, 25 (96.2%) had a primary thoracic curve. **Fig. 1a-i** shows a patient with a unilateral instrumented thoracic curve over a period of 50 months postoperative. (a) Preoperative: This 15-year-old girl (Risser 4, Sanders 7) with AIS demonstrates preoperative curves measuring 67° thoracic, 33° proximal thoracic, and 42° lumbar. (b) The preoperative lateral radiograph displays thoracic lordosis of 3°, or a calculated 3D kyphosis of -16°. (c) On the upper thoracic bend, her upper thoracic curve reduces to 7°. (d) On fulcrum bend, her thoracic curve reduces to 26°. (e) On the left bend, her lumbar curve reduces to 0°. (f) The patient underwent ASC from T5-L2 with disc release at 5 levels (T6-7, T7-8, T8-9, T9-10, T10-11). The PA first erect radiograph demonstrates a 5° curve with the maximum thoracic curve measuring 15°. (g) The first erect lateral shows restoration of kyphosis from T5-T12 to measure 26° or a calculated 3D kyphosis of 31°. (h) On the most recent PA erect radiograph at 50 months, the instrumented thoracic curve measures 21° and the maximum thoracic curve measures 23°. (i) The most recent lateral radiograph displays 2D kyphosis of 36° and 3D kyphosis of 35°. 3D kyphosis improved 51° from -16° to 35°.

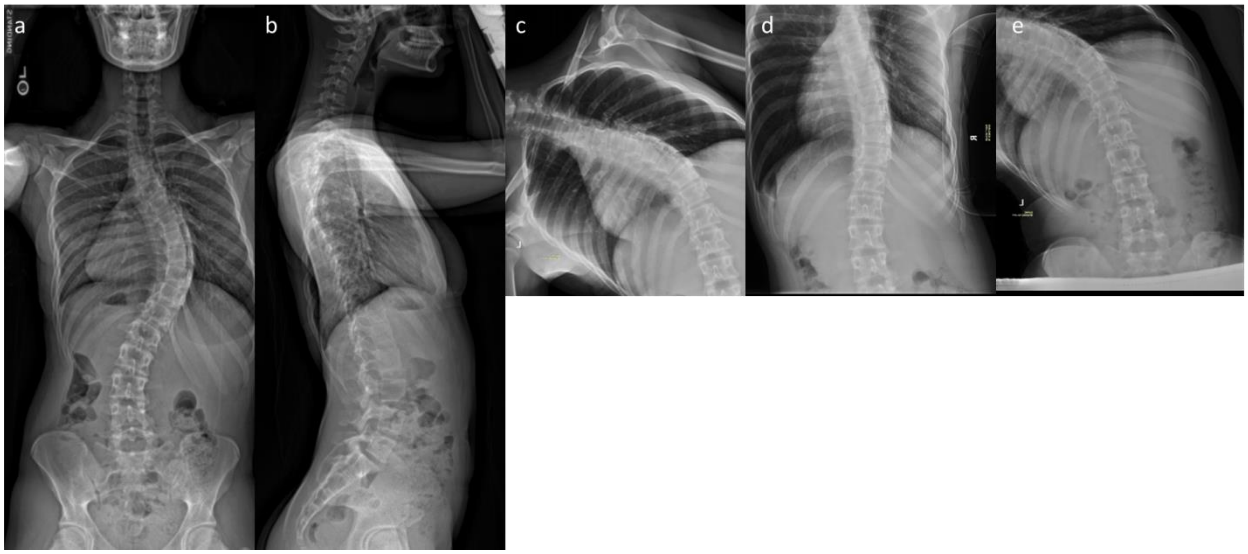


*Fig. 1a-e*

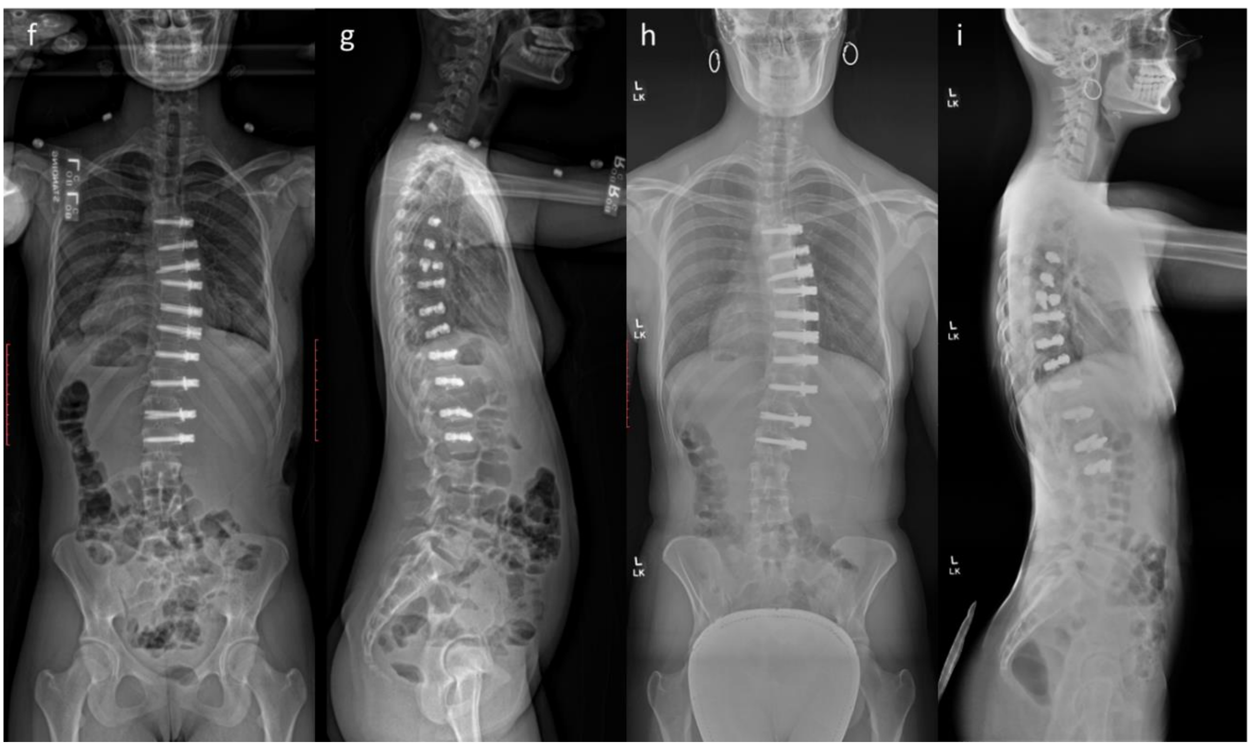


*Fig. 1f-i*

**Fig. 1a-i**. Example of unilateral instrumented thoracic curve over a period of 50 months postoperative. (a) Preoperative: A 15-year-old girl (Risser 4, Sanders 7) with AIS demonstrates preoperative curves measuring 67° thoracic. (b) The preoperative lateral radiograph displays thoracic lordosis of 3°, or a calculated 3D kyphosis of minus 16°. (c, d, e) Bend radiographs. (f, g) First erect PA and lateral radiographs. (h) The most recent PA erect radiograph at 50 months; the instrumented thoracic curve measures 21°. (i) Most recent lateral radiograph showing 3D kyphosis of 35°.

One patient (3.8%) had a double major curve pattern **(Fig. 2a-i)**. This is an example of bilateral instrumented thoracic and lumbar ASC in a 13-year-old girl (Risser 4, Sanders 7). (a) The preoperative radiograph shows thoracic and lumbar curves measuring 73° and 62°, respectively. (b) The preoperative lateral radiograph shows thoracic kyphosis of 37° in 2D, or a calculated 3D kyphosis of 8.65°. (c) The preoperative left bend film shows an upper thoracic bend curve of 4°. (d) The preoperative fulcrum bend radiograph shows a thoracic bend of 32°, which indicates 56% flexibility. (e) The preoperative left lumbar bend film shows a lumbar bend of 26°. (f) The patient underwent T6 – L4 ASC with disc releases at 5 thoracic levels. On the first erect PA radiograph, the instrumented thoracic curve measures 13° while the instrumented lumbar curve measures 9°. (g) The first erect lateral radiograph shows a thoracic kyphosis of 36° in 2D, or a calculated 3D kyphosis of 38°. (h) At the patient's 40-month postoperative (most recent) visit, the instrumented thoracic curve measures 15° while the instrumented lumbar curve measures 21°. Splaying can be seen at L1-2 and L2-3 with loss of correction of +4° in the thoracic region and +13° in the lumbar region. (i) The most recent lateral radiograph at 40-month follow-up displays a thoracic kyphosis of 35° in 2D, or a calculated 3D kyphosis of 38.4°.

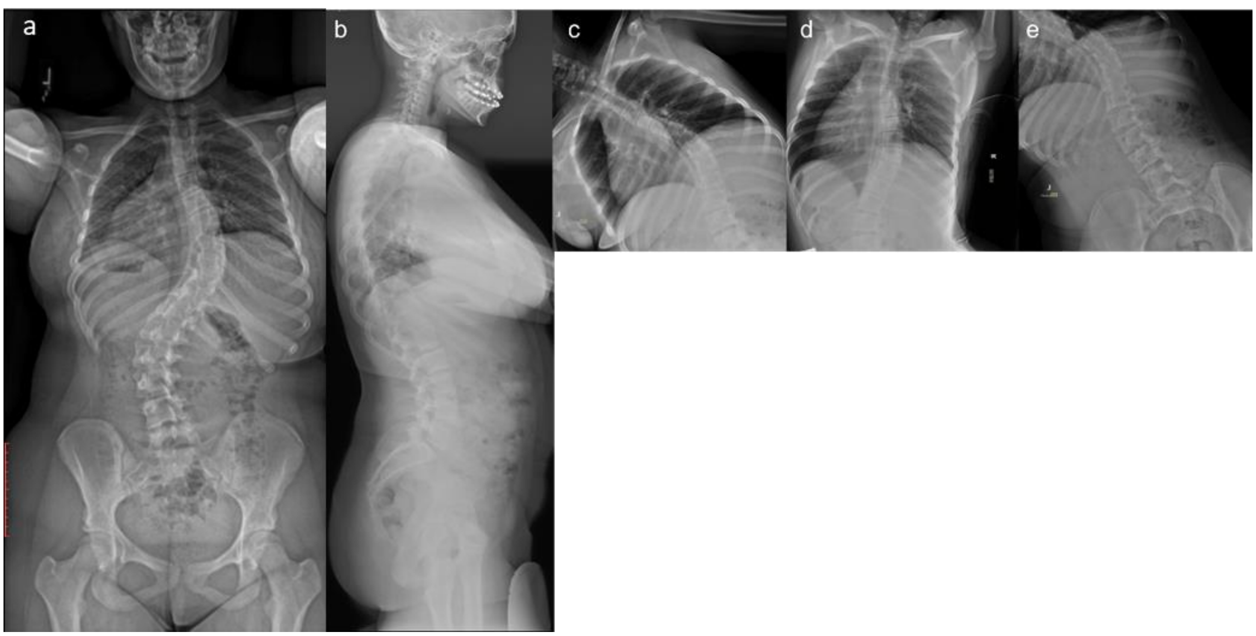

*Fig. 2a-e*

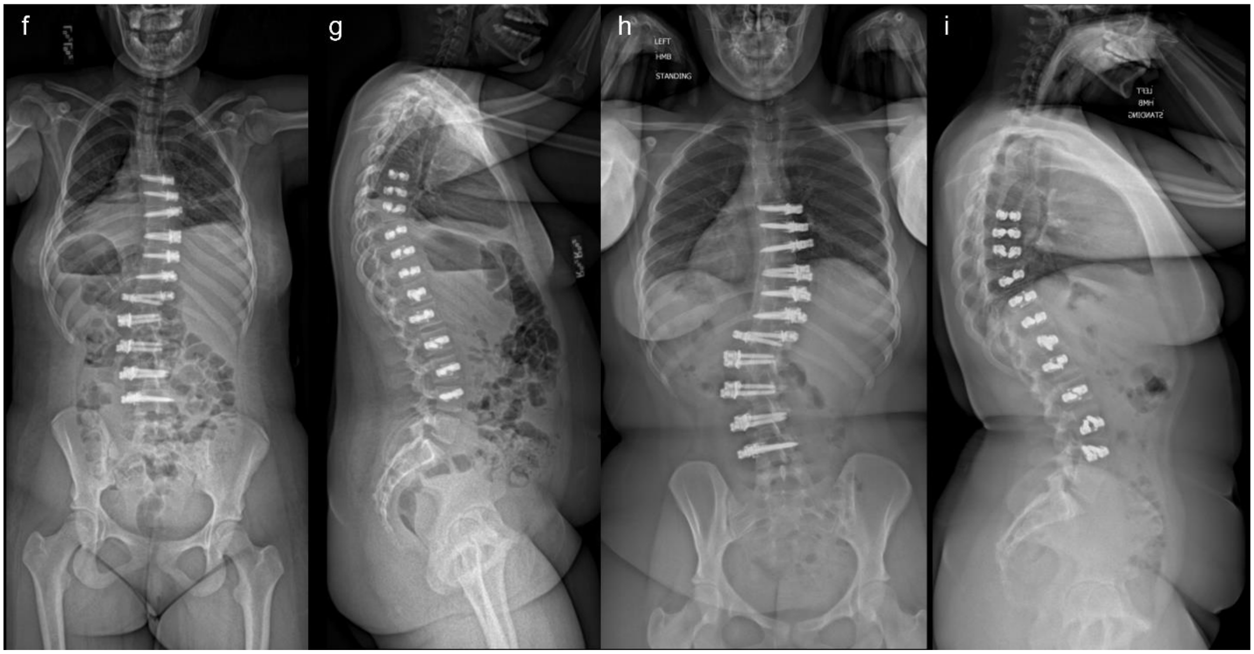


*Fig. 2f-i*

Fig. 2a-i. Bilateral instrumented thoracic and lumbar ASC in a 13-year-old girl (Risser 4, Sanders 7). (a) Preoperative radiograph shows thoracic and lumbar curves measuring 73° and 62°, respectively. (b) The preoperative lateral radiograph shows a calculated 3D kyphosis of 8.65°. (c, d, e) Bend radiographs. (f, g) The patient underwent T6 – L4 ASC with disc releases at 5 thoracic levels. (h, i) At the patient's 40-month postoperative (most recent) visit, the instrumented thoracic curve measures 15° while the instrumented lumbar curve measures 21°. Splaying can be seen at L1-2 and L2-3 with loss of correction of +4° in the thoracic region and +13° in the lumbar region. Calculated 3D kyphosis measures 38.4°.

Patient demographics are summarized in **Table 1.** At the time of surgery, 17 patients (65.4%) were considered skeletally immature (Sanders 3 ≤ 7), and 9 patients (34.6%) were considered skeletally mature (Sanders > 7).

**Table 1.** Patient Demographics

| **Patients' Curve Type, n (%)** | |
|---|---|
| Thoracic only | 25 (96.2%) |
| Thoracolumbar/Lumbar | 0 (0%) |
| Double Curve | 1 (3.8%) |
| **Sex, n (%)** | |
| Female | 22 (84.6%) |
| Male | 4 (15.4%) |
| **Age at Time of Surgery, mean ± SD (range), years** | 17.3 ± 5.4 (10.5-34.5) |

| Age at Time of Surgery | |
|---|---|
| Children (10 through 12 years) | 3 (11.5%) |
| Adolescents (13 through 17 years) | 15 (57.7%) |
| Adults (18 to 35 years) | 8 (30.8%) |
| **Preoperative Sanders Score, mean ± SD, range** | 7 ± 1.5 (3-8) |
| **Follow-up Duration, mean ± SD (range), months** | 30.8± 6.8 (24-50) |

Preoperative and postoperative curve measurements are shown in **Table 2**.

**Table 2.** Pre- and Postoperative Coronal Curve Angles for Instrumented Curves

| Instrumented Curve Type | Coronal Measurements | Percent Correction | P-value |
|---|---|---|---|
| **Thoracic (n = 26)** | | | |
| Preoperative Thoracic Curve | 74 ± 7.8° (66 – 90°) | | |
| Postoperative Thoracic Curve First Erect (Maximum) | 23 ± 5.8° (9 – 31°) | 68.9% | <0.0001[a] |
| Postoperative Thoracic Curve Most Recent (Maximum) | 26 ± 7.2° (11 – 43°) | 64.9% | <0.0001[a] |
| Postoperative Thoracic Curve First Erect (Instrumented) | 13 ± 7.3° (3 – 29°) | 82.4% | <0.0001[a] |
| Postoperative Thoracic Curve Most Recent (Instrumented) | 16 ± 9.9° (3 – 39°) | 78.4% | <0.0001[a] |
| **Lumbar (n = 4)** | | | |
| Preoperative Lumbar Curve | 59 ± 7.7° (58 – 66°) | | |
| Postoperative Lumbar Curve First Erect Maximum | 13 ± 3.9° (8 – 17°) | 78.0% | <0.0001[a] |
| Postoperative Lumbar Curve Most Recent (Maximum) | 22 ± 9.3° (8 – 29°) | 62.7% | <0.0001[a] |
| Postoperative Lumbar Curve First Erect (Instrumented) | 12 ± 6.4° (5 – 12°) | 79.7% | <0.0001[a] |
| Postoperative Lumbar Curve Most Recent (Instrumented) | 17 ± 8.5° (7 – 27°) | 71.2% | <0.0001[a] |

[a] One-tailed paired t-test.

For thoracic curves the most superior thoracic level to be instrumented was T3 and the most inferior instrumented level was L2. For lumbar curves the most superior was T12 and the most distal was L4. Data on anterior longitudinal ligament complex releases are shown in **Table 3**.

**Table 3.** Anterior Longitudinal Ligament Complex Releases in Instrumented Thoracic Curves

| | |
|---|---|
| Thoracic curves, n | 26 |
| Patients, n (%) | 26 (100%) |
| Releases, n | 106 |
| Mean per case (range) | 4.1 (1 – 6) |

*3.2. Radiographic Results*

### 3.2.1 Maximum Instrumented Coronal Curve Angle

In the 26 patients with instrumented thoracic curves, the average preoperative curve of 74° (range 66 to 90°) was corrected to an average postoperative coronal curve angle of 16° (range 3° to 39°) in the instrumented curve (average 78.4% correction). The maximal thoracic coronal curve corrected to 26° (range 11° to 43°) postoperatively (average 64.9% correction) ($p < 0.0001$). In the 4 patients with instrumented lumbar curves, the average preoperative curve of 59° (range 58° to 66°) was corrected to an average postoperative coronal curve angle of 17° (range 7° to 27°) in the instrumented region (71.2% correction) and to 22° (range 8° to 29°) in the maximum lumbar curve (62.7% correction) ($p < 0.0001$).

Clinical success with residual curves ≤ 35° was 96% (25/26) in all patients and 92.3% in those with curves measuring ≤ 30° (24/26). Those with thoracic curves not achieving clinical success include one patient with a preoperative severe thoracic curve of 86° and a postoperative instrumented thoracic curve of 39° and another patient with a preoperative curve of 66° and a postoperative curve of 33°. Removal of instrumentation to decrease overcorrection (3.8%) was recommended in one patient but not performed.

### 3.2.2. Thoracic Kyphosis

Analysis of kyphosis was performed on 25 patients. One patient was excluded from this analysis due to preoperative hyperkyphosis of 54°. This patient had too much preoperative kyphosis and in retrospect an ASC would not have been recommended. In the 25 patients, preoperative 2D kyphosis on sagittal imaging showed an average value of 21.6° ± 13.4° (range: 1° to 46°). Postoperative 2D kyphosis on the most recent follow-up radiographs and measured an average of 37.9° ± 12.4° (range: 11.4° to 61°) **(Table 4)**.

**Table 4.** 2D Kyphosis Measurements

| 2D kyphosis, Mean ± SD (Range), Degrees | Preoperative Measurements | Postoperative (> 2 Years) Measurements | |
|---|---|---|---|
| Patients (n=25) | 21.6 ± 13.4° (1 – 46°) | 37.9 ± 12.4° (11.4 – 61°) | <0.0001[a] |

[a] One-tailed paired t-test.

Calculated 3D kyphosis was determined to measure a preoperative average of -4.2° ± 11.3° (range: -19.6° to 18.9°) and a postoperative average at most recent follow-up of 34.8° ± 11.0° (range: 10.6° to 54.8°) **(Table 5)**.

**Table 5.** 3D Kyphosis Measurements

| 3D kyphosis, mean ± SD (range), degrees | Preoperative Measurements | Postoperative (> 2 years) Measurements | |
|---|---|---|---|
| Patients (n=25) | -4.2 ± 11.3° (-19.6 – 18.9°) | 34.8 ± 11.0° (10.6 – 54.8°) | <0.0001[a] |

[a] One-tailed paired t-test.

For preoperative and postoperative calculated 3D kyphosis, we found an average of 39° ($p < 0.0001$) improvement in hypokyphosis after ASC **(Fig. 3)**. This is a 15-year-old girl with a thoracic Lenke 2 curve having ASC with correction of thoracic lordosis. (a) The preoperative PA radiograph shows curves of 83° thoracic, 42° lumbar, and 49° upper thoracic. (b) The preoperative lateral radiograph shows a preoperative 2D kyphosis of 24° and a calculated 3D kyphosis of -7.° (c) A fulcrum bend test shows a thoracic bend curve of 37°, which indicates 55% flexibility. (d) The left upper thoracic bend is reduced to 27°. (e) The left lumbar bend shows a lumbar bend curve of 0°. (f) This is the PA at first erect radiograph after undergoing T5 – L1 ASC with disc releases at 4 levels. (g) At first erect follow-up 6 days after surgery, the instrumented thoracic curve measures 6°. (h) At the patient's 24-month postoperative visit, the instrumented thoracic curve measures 23° with no cord breakage. (i) The 24-month lateral radiograph shows postoperative 2D kyphosis of 35° and calculated 3D kyphosis of 34.1°.

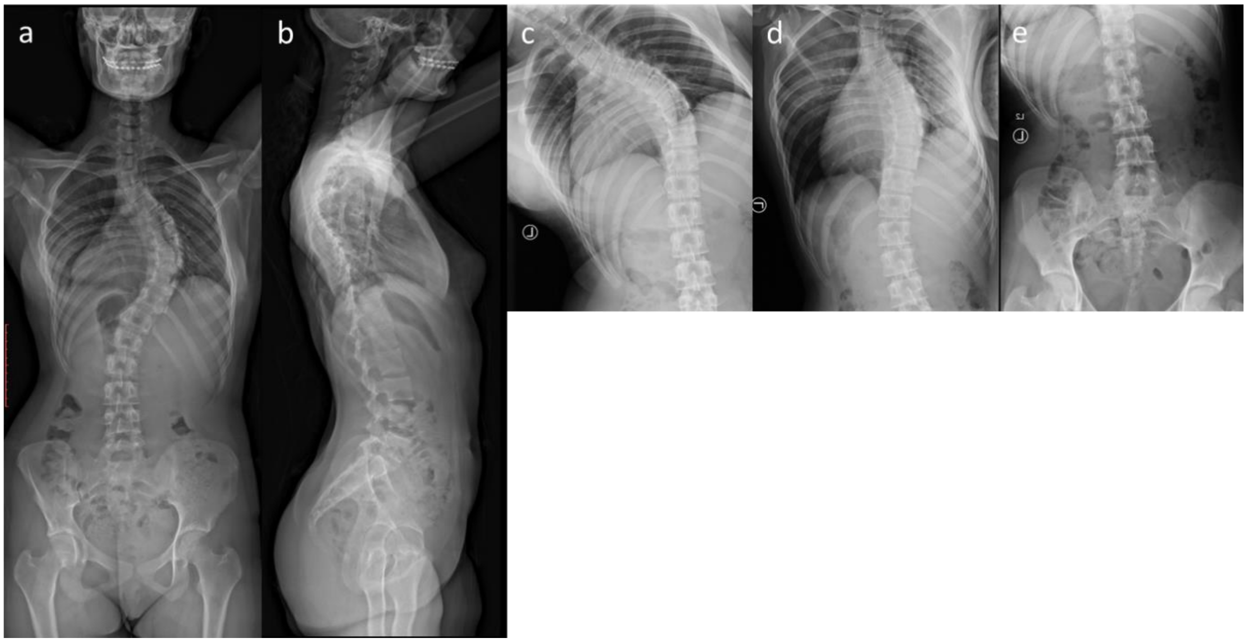


*Fig. 3a-e*

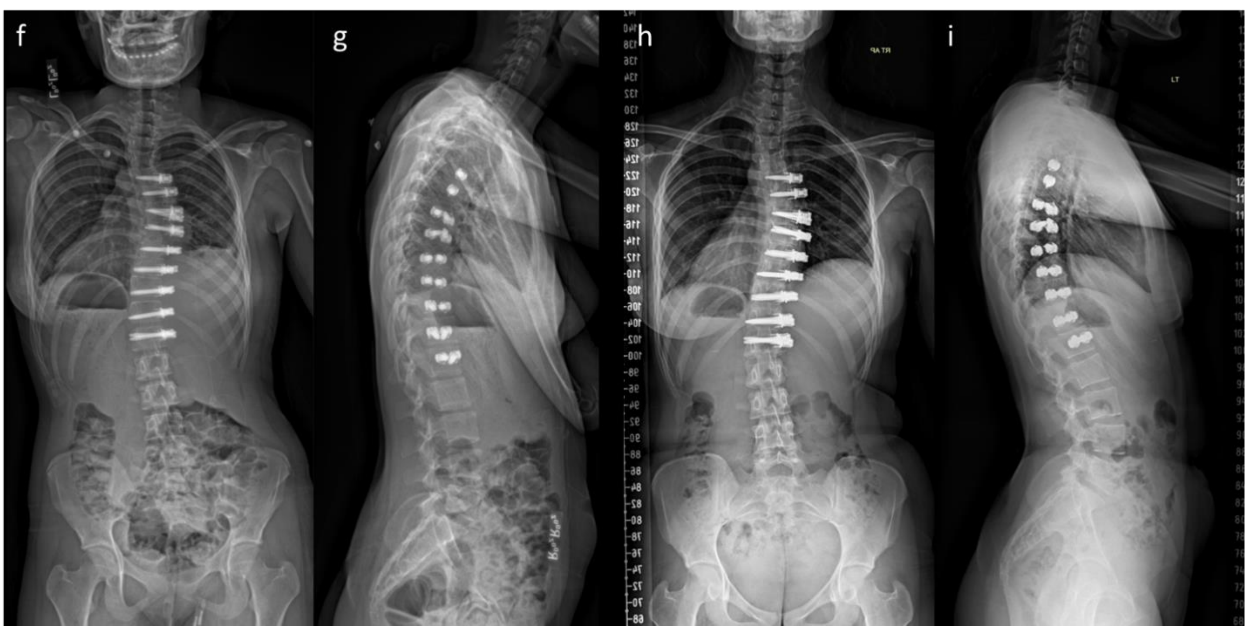


*Fig. 3f-i*

Fig. 3a-i. (a) 15-year-old girl with thoracic Lenke 2 curve who underwent ASC with correction of thoracic lordosis. (a) The preoperative PA radiograph shows curves of 83° thoracic. (b) The preoperative lateral radiograph shows preoperative calculated 3D kyphosis of -7.° (c, d, e) Bend radiographs. (f) First erect PA radiograph after undergoing T5 – L1 ASC with disc releases at 4 levels. (g) First erect lateral radiograph. (h) At the 24-month postoperative visit the instrumented thoracic curve measures 23° with no cord breakage. (i) The calculated 3D kyphosis measures 34.1°.

An additional 3 patients had large compensatory lumbar curves requiring instrumentation. Therefore, there were a total of 26 thoracic curves and 4 lumbar curves for analysis. The thoracic curves include some Lenke 2 curves.

#### 3.2.3. Analysis of Screw Position for Possible Cord Breakage

Based on a > 5° increase in angulation between 2 adjacent screws, described by Newton et al.,[13] splaying was observed radiographically in 14 of the 26 patients (53.8%). In 8 of the 14 patients, splaying occurred at only one level (57.1%). In the remaining 6 patients, (42.9%) splaying occurred at ≥ 2 levels. In total, there was splaying at 13 thoracic levels and 6 lumbar (**Table 6**).

**Table 6.** Overall Construct Splaying

| | |
|---|---|
| Patients with Construct Splaying (n) | 14 (53.6%) |
| One level (n) | 8 (57.1%) |
| Two levels (n) | 6 (42.9%) |
| Curves with Construct Splaying (n) | 19 |
| Thoracic (n) | 13 (68.4%) |
| Lumbar (n) | 6 (31.6%) |

In the thoracic region, T11-T12 was the most common level (n = 8, 61.5%), followed by T12-L1 (n = 3, 23.1%) and then T10-11 (n = 1, 7.7%) and T6-7 (n =1, 7.7%). In the lumbar region, L1-2 was the most common level (n =3, 50%), followed by L2-3 (n = 2, 33.3%) and L3-4 (n = 1, 16.7%) (**Tables 7 and 8**).

Construct splaying in the thoracic region is shown in **Table 7**. In the thoracic region, average loss of correction was 8.2° ± 6.5°. Of those, only one patient had loss of correction > 15° (24°). The majority lost clinically insignificant curve correction. One patient had loss of correction of 11-15°, three had loss of correction of 6-10°, and five had loss of correction of < 5°.

**Table 7.** Construct Splaying in the Thoracic Region

| Total Number of Thoracic Construct Splaying (n) | 13 |
|---|---|
| T6-7 | 1 (7.7%) |
| T10-11 | 1 (7.7%) |
| T11-12 | 8 (61.5%) |
| T12-L1* | 3 (23.1%) |
| **Loss of Correction in Thoracic Region mean ± SD** | **8.2° ± 6.5°** |
| < 5° (n) | 5 (50%) |
| 6-10° (n) | 3 (30%) |
| 11-15° (n) | 1 (10%) |
| >15° (n) | 1 (10%) |

*Note: Considered thoracic as all splaying at T12-L1 occurred on the thoracic side of the curve

Construct splaying in the lumbar region is shown in **Table 8**. In the lumbar region average loss of correction was 10.5° ± 4.8°. Of those, three had loss of correction of 11-15° and one had loss of correction of < 5°. For this cohort no lumbar anterior longitudinal ligament and disc complex releases were performed. For this reason, patients were more likely to experience slight loss of correction with cord splaying. Current practice involves anterior longitudinal ligament and disc complex releases in both the thoracic and lumbar spine.

**Table 8.** Construct Splaying in the Lumbar Region

| Total Number of Lumbar Construct Splaying (n) | 6 |
|---|---|
| L1-2 | 3 (50%) |
| L2-3 | 2 (33.3%) |
| L3-4 | 1 (16.7%) |
| **Loss of Correction in Lumbar Region mean ± SD** | **10.5° ± 4.8°** |
| < 5° (n) | 1 (25%) |
| 6-10° (n) | 0 (0%) |
| 11-15° (n) | 3 (75%) |
| > 15° (n) | 0 (0%) |

#### Overcorrection

One patient experienced overcorrection of the distal curve segments. Another who initially overcorrected benefited from cord breakage which decreased their overcorrection.

### *3.3. Adverse Events*

No intraoperative adverse events were seen in this series of 26 patients. Only 3 patients (11.5%) had postoperative events, including 2 patients with moderate delayed pleural effusions and 1 with kyphosis. Both pleural effusions were identified on the patients' 6-week postoperative radiographs, and both resolved spontaneously without intervention by the 3-month postoperative radiograph (Clavien-Dindo-Sink [CDS] Class 1). Similarly, no interventions were attempted in the one instance of postoperative kyphosis (CDS Class 1). No patients in this study required a revision or repeat surgical intervention.

Two patients experienced overcorrection following ASC. One underwent extensive bracing for one year in order to prevent progression, and removal of instrumentation at T11-L2 was eventually recommended. However, the removal was not performed. Another patient initially overcorrected; however, this was reversed following cord breakage.

## 4. DISCUSSION

The Anterior Scoliosis Correction (ASC) procedure for the treatment of severe thoracic curves (> 65°) in patients with idiopathic scoliosis successfully corrected scoliotic curves to ≤ 30° in 92.3% of our patients. The 2 thoracic residual curves measured 39° from 86° preoperative in one patient and 33° from 66° preoperative in another patient.

Currently, treating severe curves in the range of 66° to 90° by VBT is not possible after reported, therefore, articles addressing this cohort of patients with VBT do not exist in the literature. Thus, direct comparison for effectiveness in treating AIS patients with the ASC procedure described here against VBT is not feasible. However, we included a few studies on treatment of VBT with skeletally immature AIS patients with moderate curves below for reference **(Table 9)**.

Table 9. Clinical Success Rates

| | Antonacci et al. | Hoernschemeyer et al.[22 a] | Samdani et al.[21 a] | Rushton et al.[25a] | Newton et al.[23a] | Miyanji et al.[24a] | Newton et al.[34] | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | VBT | PSF |
| No. Patients | 26 | 25[b] | 56 | 112 | 23 | 57[c] | 108 | 108 |
| Mean Follow-up (Range), months | 30.3 ± 5.8 (24 – 40) | 34.1± 10.0[b, d] (17 – 62) | 55.2 ± 12.5 (33 – 78) | 37 ± 9 (15 – 64) | 40.8 ± 13.2 (24 – 60) | 40.4 ± 9.3 (11 – 56)[b] | 26.4 ± 6 (21.6 – 67.2) | 28.8 ± 6 (21.6 – 63.6) |
| Avg. Preop. Thoracic Curve | 74° ± 7.8° (66°- 90°) | 46° ± 10°[b] (26°-70°) | 40° ± 7° | 51°± 10° (31°-81°) | 53° ± 8° (41°-67°) | 51° ± 11° (31°-81°) | 52° ± 9° | 52° ± 8° |
| Avg. Postop. Thoracic Curve (Most Recent Instrumented) | 16 ± 9.9° (3 – 39°) | 21 ± 9°[b] (-5 ± 35°) | 19 ± 13° | 26° ± 10° (31 – 81°) | 33° ± 18° (-5 – 62°) | 23° ± 15° (-18 – 57°) | 30° ± 11° | 19° ± 7° |
| Overall % Correction | 78.4% | 54.3%[b] | 52.5% | 49.6% | 37.8% | 42.9% | 41% | 63% |
| Clinical Success (≤ 30°) | 92.3% | 74% (n = 27)[e] | 80%[f] | N/A | N/A | N/A | N/A | N/A |
| Clinical Success (≤ 35°) | 96% | N/A | N/A | 71% | 52% | 77% | 67% | 97% |
| Revision Rate % (n) | 0% (0) | 22.2% (6) | 12.3% (7) | 12.8% (15) | 30.4% (7) | 14.0% (8) | 10% | 2% |

[a] Studies include skeletally immature patients only, whereas Antonacci et al. includes both skeletally immature and mature patients (Sanders Stage 8, n=2).
[b] Hoernschemeyer et al. indicated 27 patients in their study; however, Table 1 indicated exclusion of Patients 3 and 5. Also, the studies did not calculate the average value with all patients, but rather subdivided based on curve type. Therefore, we recalculated the aggregative value with omission of Patients 3 and 5.
**Pre-op = 100 – 40 / 100 (pre – post-op/pre) x 100 → Avg, STDEV, range
[c] Miyanji et al. included 2 patients who underwent posterior fusion within 2 years of follow-up.
[d] Hoernschemeyer et al. included one patient (No. 14) with follow-up at 1.4 year according to supplementary figure.
[e] Hoernschemeyer et al. reported clinical success based on all 27 patients. Of noted, Hoernschemeyer et al. included patients with non-structural thoracic curve (Lenke 5) in their patient population, whereas Antonacci et al. did not.
[f] Samdani et al. 61% success over 45°

The majority of studies to date have utilized ≤ 30° as a marker of clinical success at final follow-up in patients undergoing VBT. Samdani, et al.[21] demonstrated an 80% success rate (< 30°) at final follow-up in 45 of 56 patients treated. Of note, Samdani's study had an average preoperative thoracic curve of only 40° ± 7°. The success rate in Samdani's VBT study was much lower when stratified for higher curves. Our study has a mean preoperative curve at least 34° greater. Hoernschemeyer et al.[22] describe a clinical success rate of 74% (< 30°) in 27 skeletally immature AIS patients with average preoperative curves of only 46° but also included patients with non-structural thoracic curves (Lenke 5).

Newton, et al.[23] found that 52% of patients with preoperative average curves of 53° with 2-year minimum follow-up had radiographic success. Miyanji et al.[24] reported on a cohort of 57 patients with preoperative curves averaging 51° as having a 77% success rate. Rushton et al.[25] reported a 71% clinical success rate for 112 treated patients with average preoperative curves of 51°. However, all three of these VBT reports used < 35° instead of < 30° as the measure for clinical success. If our study defined clinical success as < 35°, our clinical success rate would have been 96% (25/26).

We believe that the magnitude of correction using our proprietary technique of ASC (78.4% correction) in this series of patients with severe curves (average preoperative thoracic curve sizes of 74°) are better than those using VBT (which treats small to moderate curves) because of the additional techniques employed at the time of surgery to obtain an active rather than passive correction. Unlike VBT, ASC does not rely primarily on growth modulation to correct the scoliosis. Our primary surgeon (M.D.A.) currently employs a modified mini-open anterior fusion approach, with anterior longitudinal ligament complex (ligament, annular capsule, and disc) releases of nearly all levels, along with double rod-cord and double-screw-line constructs to improve derotation and overall curve correction. This is supported by our previous work on mature patients with AIS where the average coronal correction was 65.5% for thoracic curves and 66.7% for lumbar curves. Of those patients, 71.4% with thoracic curves received at least 1 thoracic disc release.[16] Furthermore, this technique diminishes the loss of correction intraoperative to first erect radiographs seen in single screw /rod-cord cases because of the rotational stability with the double screw / double rod-cord construct.

Additionally, preliminary evidence suggests that the primary surgeon's (M.D.A.'s) use of a double rod-cord with double screw-line technique can reduce the construct splaying risk from > 25% to 16% during the first year.[26] In addition to the dual construct, the authors hypothesize that performing anterior longitudinal ligament complex (ligament, annular capsule, and disc) releases at nearly all levels in all patients leads to more powerful sagittal and coronal corrections with significant derotation. Further, they enhance long-term stability of the corrected curves through multi-level tissue healing and remodeling in the corrected position, which thereby impedes late curve decompensation.[27] (The authors' preliminary clinical data using postoperative MRI analysis, combined with clinical experience of over 7 years performing the multi-level releases and staged approaches, supports that anterior longitudinal ligament and annular disc rehealing does occur, provides for greater correction and improved long-term mechanical stability, and does so without development of discogenic pain issues). Lastly, Pehlivanoglu et al.[28] demonstrated that the mini-open approach provided superior growth modulation resulting in 80% thoracolumbar correction and 82% lumbar correction in comparison to 64% thoracolumbar correction and 69% lumbar correction of endoscopic cases at 2-year follow-up, respectively.

Generally, thoracic hypokyphosis is not corrected with VBT. In our series reported here and previously,[16] the use of anterior longitudinal ligament complex (ligament, annular capsule, and disc) releases, along with corrective force across the anterior column of the thoracic spine, result in improved kyphosis towards normality.[29] In that study, kyphosis (T5-T12) calculated 3D corrected from average 2° preoperative to 34° postoperative. In this current study, average 3D kyphosis changed from -4.2° ± 11.3° to 34.8°± 11, an improvement of 39°. We suggest that the significant improvement in kyphosis is due to the effect derotation as a consequence of anterior longitudinal ligament complex (ligament, annular capsule, and disc) releases, which allow for effective correction of the lordotic thoracic spine and thus sagittal compensation. Previous work has shown that correction of the thoracic spine kyphosis to > 30° may have a positive influence by improving cervical lordosis.[30, 31]

No patients in this study had a revision, but removal of instrumentation due to overcorrection was recommended in one (but never performed). Comparatively, Newton et al.[23] in their series of VBT for immature patients demonstrated a 30.4% (7/23) revision rate, with 3 patients requiring tether removal due to overcorrection and 1 patient requiring removal of the tether due to progression of the lumbar curve. In addition, 1 tether was replaced with less tension due to overcorrection, 1 required retethering of a broken cord, and 1 was converted to PSF. The Newton et al.[23] study reports that at latest follow-up, 2 additional patients were indicated for conversion to PSF and were considered both failures of treatment and unanticipated revisions, for a total 39.1% (9/23) VBT failure rate. This difference may be due to the larger residual postoperative curves remaining at the time of surgery and longer follow-up. ASC is a de-tethering technique which utilizes multi-level anterior longitudinal ligament, annular, and disc complex releases to obtain the desired residual curve instead of allowing the stiffness of the curve to dictate the amount of correction on the table. Similarly, in a VBT study by Miyanji et al.,[24] 9 patients (15.8%) underwent an unplanned revision, with 3 patients undergoing revision of the tether and 6 converted to metal rod fusion due to insufficient correction of tethered curve, progression of deformity, and adding on.

In a recent meta-analysis, the incidence of postoperative complications revealed that patients with VBT who had a follow-up time of < 36 months experienced a 23.79% rate (95% CI: 8.67%–38.92%), while those with a follow-up time of > 36 months had a 52.17% rate (95% CI: 33.71%–70.64%).[32] A subanalysis of all postoperative complications using the Clavien-Dindo-Sink (CDS) Classification demonstrated that the incidence rate of Grade II CDS complications was 25.87% (95% CI: 14.8%– 36.94%%) for < 36 months and 36.79% (95% CI: 18.53%–55.05%) for > 36 months. For Grade III CDS complications, the overall incidence rate was 8.92% (95% CI: 5.75%–12.09%), with 3.2% (95% CI: 1.74%–4.66%) for < 36 months and 16.05% (95% CI: 12.53%–19.58%) for > 36 months. For Grade IV CDS complications, the overall incidence rate was 0.37% (95% CI: 0%–1%), with 0.37% (95% CI: 0%–1.18%) observed in patients with < 36 months of follow-up and 0.36% (95% CI: 0%–1.35%) in those with > 36 months.

Notably, this meta-analysis did not evaluate the incidence rate of Grade I CDS complications. In comparison, our cohort included 17 patients who developed postoperative complications, all classified as CDS Grade I. Among these patients, 14 experienced construct splaying, 2 had self-resolving postoperative pleural effusions, and 1 developed kyphosis. No Grade II or higher postoperative complications were observed. Furthermore, no revisions were required, and there were no instances of deep vein thrombosis, pulmonary embolism, or mortality. Considering the relatively short mean follow-up time of 30.3 ± 5.8 months in our cohort, we will continue to closely monitor the development of any complications.

Only a few studies have explored spinal mobility after VBT. One prospective study[33] utilized flexion-extension and side bending radiographs in 32 patients with AIS who underwent thoracic VBT. The results demonstrated maintenance of both coronal and sagittal arc of motion after one year postoperatively, which provides proof of concept that sagittal spinal motion is preserved after thoracic anterior VBT, although the functional importance remains to be determined. Future study should focus on clinical spinal motion and patient-reported outcomes between patients undergoing ASC or PSF to investigate whether the residual spinal motion correlates to patient ability in activities of daily living.

The authors acknowledge that this study has significant limitations but felt it important to report these early results in patients with severe curves as the literature is currently nonexistent. The relatively small sample size of the cohort and reporting on the proprietary data from only one primary surgeon (M.D.A.) may have decreased the margin of error as well as the generalizability of the results to other surgeons. Conversely, this enables consistency of surgical technique and postoperative care. As this is a retrospective study, there is an inferior level of evidence compared with prospective studies, and there exists the possibility of selection bias, recall bias, or misclassification bias. Other limitations include lack of patient-reported outcomes, lack of a concurrent comparison cohort with VBT and PSF, and a relatively short follow-up (2-4 years).

## 5. CONCLUSION

In conclusion, the concept of the Anterior Scoliosis Correction (ASC) procedure is different than that of VBT in that ASC is a de-tethering technique that utilizes soft tissue anterior longitudinal ligament, annular, and disc complex releases while preserving the cartilaginous endplates to achieve a greater magnitude of deliberate correction. It is performed through a modified anterior fusion approach using an anterior muscle-sparing thoracotomy which allows for significant derotation, preservation of segmental blood supply, and multi-screw, multi-cord constructs. ASC therefore has the potential for much expanded indications and increased ability for correction in that the releases eliminate the limitation of curve severity in VBT procedures to small or moderate curves in patients with growth remaining. In our cohort with minimum 2-year follow-up, ASC for the treatment of 26 AIS patients with severe thoracic curves (between 65° and 90°) resulted in curve correction of 78.4%, and the clinical success was 96% for curves measuring ≤ 35°. Significant improvement of preoperative hypokyphosis was seen, from an average of -4° to 35°. There were no revisions performed on these patients at current follow-up.

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