Anterior Lumbar Vertebral Body Tethering in Adolescent Idiopathic Scoliosis

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Abstract: Adolescent idiopathic scoliosis (AIS) is the most common spinal deformity in children. The traditional treatment for curves greater than 50 degrees is posterior spinal fusion with instrumentation for correction and prevention of curve progression later in life. However, there is growing interest in non-fusion techniques such as anterior vertebral body tethering. Despite the common presentation of thoracolumbar and lumbar curves in AIS, descriptions of anterior vertebral body tethering for AIS have been largely limited to the thoracic vertebrae. The goal of this paper is to describe the technique of lumbar anterior vertebral body tethering (AVBT) which involves a combined thoracoscopic and mini-open approach to the spine with a transdiaphragmatic tether. The technique and reduction are aided by CT navigation and a radiolucent hinged spine surgery table.

Key Concepts:

- Advantages of lumbar anterior vertebral body tethering (AVBT) include correction of scoliosis, preservation of lumbar spine mobility while maintaining growth potential.
- Challenges of lumbar AVBT include safe exposure of the screw starting point, determination of the appropriate screw trajectory given vertebral rotation and spinal mobility, and passage of the cord through the diaphragm.
- An experienced approach surgeon should be enlisted to help avoid potential complications, which include injury to viscera, solid organs, ureter, lumbosacral plexus, or lymphatic system.
- Surgeons should attain expertise with thoracic AVBT before transitioning to lumbar AVBT.

Introduction

Scoliosis is defined by spinal curvature greater than 10 degrees and has been reported to affect 1-3 in 1,000 adolescents at the time of skeletal maturity.[1,2] Adolescent idiopathic scoliosis (AIS) comprises those curves found later in childhood which are not associated with an underlying congenital malformation, syndrome, or neuromuscular condition. Mild or moderate curves in AIS patients can be observed or successfully treated nonoperatively with bracing.[3] Surgery, however, is recommended for patients with severe curves greater than 40-50 degrees to prevent curve progression. Surgical correction of AIS can be achieved either from an anterior or posterior approach.[4] Traditional surgical management of AIS typically involves posterior spinal fusion with instrumentation to achieve excellent correction. Posterior spinal fusion (PSF), however, has long-term consequences in a young patient, including decreased range of motion, pseudarthrosis, proximal junctional kyphosis, instrumentation failure, and blood loss.[5,6] Given the success of bracing and the common practice of growth modulation for the treatment of angular limb deformity, there is interest in similar non-fusion surgical procedures to correct adolescent idiopathic scoliosis while preserving motion.

The most common non-fusion technique for correcting AIS is anterior spinal tethering, which leverages the Heuter-Volkmann principle to alter longitudinal bone growth (Figure 1). Compression on the convexity can restrict growth and allow the concave side to increase in longitudinal growth, thus reducing vertebral wedging. Prior translational science publications have demonstrated the validity of this approach.[7,8] Several series have been published on the outcomes of anterior vertebral body tethering that demonstrate generally successful outcomes.[9-11]

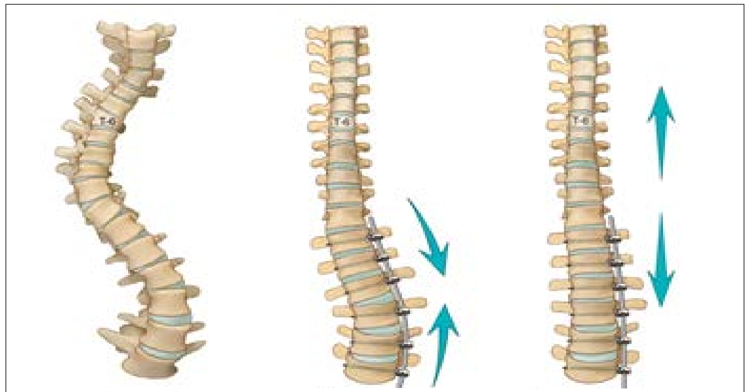


Figure 1*. Spinal application of the Heuter-Volkman principle. Compression on the curve convexity limits longitudinal growth and enables relative lengthening of the concave side, allowing for correction of spinal scoliosis.*

Figure 2A and 2B. *Patient positioning on the hinged operating table. Plastic tape secures the upper chest, hip, and thigh to the table.*

While thoracic curves are most common in AIS at 48%, the incidence of thoracolumbar or lumbar curves is the second most common at 40%.[12] Further, due to increased motion in the lumbar compared to the thoracic spine,[13-15] lumbar non-fusion technology potentially provides more benefit to the patient. The authors provide their technique for thoracolumbar anterior body tethering for correction of AIS. In August 2018, a device for anterior vertebral body tether received humanitarian device exemption approval for AIS from the U.S. Food and Drug Administration (FDA). Thus, as the technique is being more widely applied, we sought to provide a detailed account of the technique for lumbar anterior vertebral body tethering.

Patient Selection and Preoperative Planning

Current FDA indications for anterior vertebral body tethering include skeletally immature patients with curves between 30 to 65 degrees, although in our practice, patients with curves between 30 to 40 degrees are typically treated with bracing. Patient evaluation

Figure 3. *Surgeon positioning—Surgeons stand on anterior and posterior sides of the patient with ergonomically placed monitors for CT navigation and thoracoscopy.*

begins with a thorough history and physical exam to rule out non-idiopathic causes and elicit information regarding prior scoliosis treatment. Assessment of growth potential with a single posteroanterior (PA) hand film for Sanders Maturity Scale (SMS) staging as well as visualization of the pelvic apophysis for Risser staging is essential. Complete radiographic assessment with full-length scoliosis PA, side bending, and lateral films is required to characterize the curve. Because of the limits of tethering to correct kyphosis, hyperkyphosis is a contraindication to tether, particularly for thoracic curve patterns. In addition to the requirement that the patients still have growth remaining, the scoliosis curve must be flexible as well. The assessment is done via bending films and lateral bending over a bolster for thoracic curve patterns. If a curve remains greater than 30 degrees on bending films, then AVBT may not be successful, particularly if there is limited growth remaining. All surgeries at our institution are carried out in conjunction with a general surgeon specialized in the thoracoscopic and retroperitoneal approach.

The authors' current radiographic indications are a minimum of 1-year remaining growth—Risser stage <3

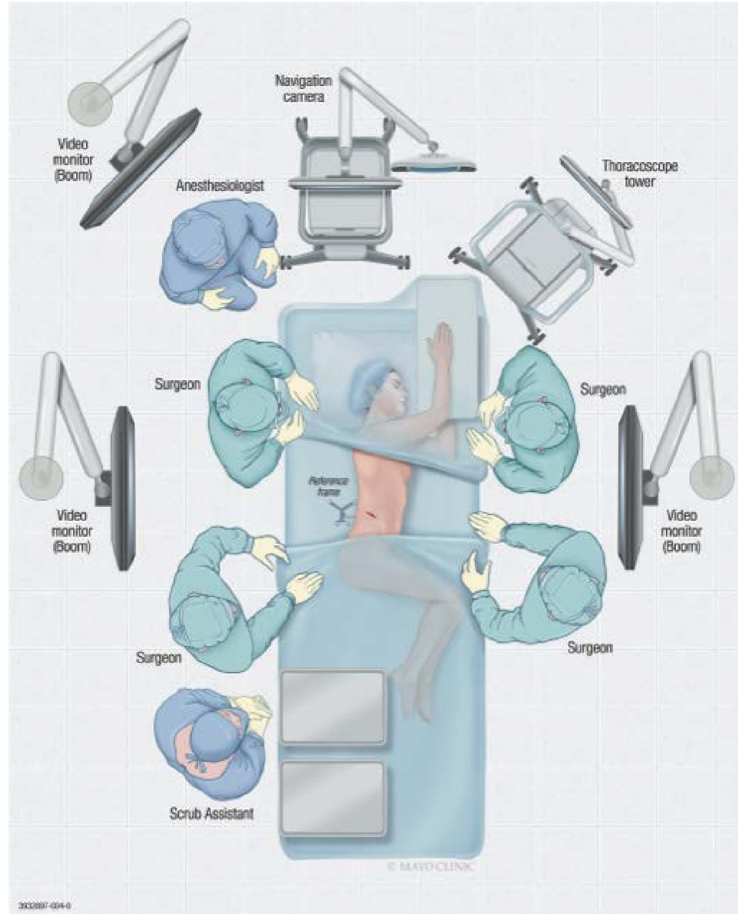


Figure 4. *An aerial view of operating room setup. Surgeons stand on opposite sides of table with paired video monitors and thoracoscopic tower positioned in clear view.*

or modified Tanner-Whitehouse score <6 (generally girls age <13 years and boys age <15 years), curve maximum Cobb angle 40-65 degrees, which decreases in magnitude below 30 degrees on bending films, and no kyphosis in the lumbar spine or at the thoracolumbar junction.

Complications of lumbar anterior vertebral body tethering include overcorrection, undercorrection, cord breakage, and progression of the deformity in the thoracic spine. Additional complications have been described with the approach. These include pneumothorax, hemothorax, chylothorax, chest wall pain, dural leak and injury to vasculature, spinal cord, ureters,[16] viscera, visceral injury, and lumbosacral plexus.[17] In our experience, most patients following lumbar tether placement have transient ipsilateral thigh numbness and occasional hip flexor weakness, which has resolved in the postoperative period. A warm foot secondary to dissection over the sympathetic chain has been noted but is less common. Thus, at L2, 3, and 4 vertebral levels, visualization of the starting point for screw placement or EMG stimulation for an MIS approach is essential to ensure patient safety for this procedure.

Description of the Method

Setup

Our surgical setup requires video-assisted thoracic surgery (VATS) equipment, double-lumen intubation, neurophysiologic monitoring, and intraoperative computed tomography-guided navigation (O-arm and Stealth, Medtronic). In addition to motor-evoked and somatosensory-evoked potentials (MEPs and SSEPs), lower extremity EMG monitoring is typically performed to avoid injury to the lumbosacral plexus. The patient is placed and stabilized in a lateral decubitus position with apex of the curve facing up on a radiolucent, hinged operating table. The patient is held in place with well-padded supports around the pelvis and arm and reinforced with athletic tape (Figure 2A and 2B).
The hips are flexed at least to 70 degrees to take pressure off the lumbosacral plexus and reduce tension on the psoas muscle. The apex of the curve is centered over the hinge to allow for intraoperative indirect correction of the scoliosis after the screws are placed. In order to facilitate exposure, particularly if an L4 screw is planned, the table needs to be extended so that the orthogonal trajectory to the L4 vertebral body screw is not blocked by the iliac crest. The pelvis is secured by a hip rest and large gel roll to eliminate intraoperative motion. After the table position has been finalized, the patient is then securely taped to the table below the hinge with 3-inch athletic tape directly on the skin. For lumbar AVBT, a second broad section of tape is also

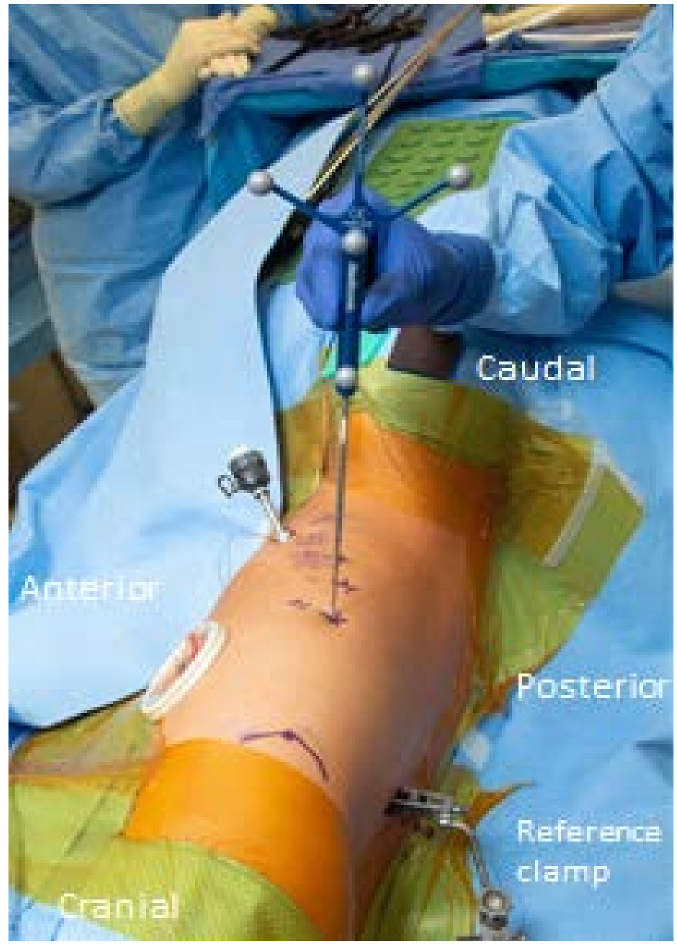
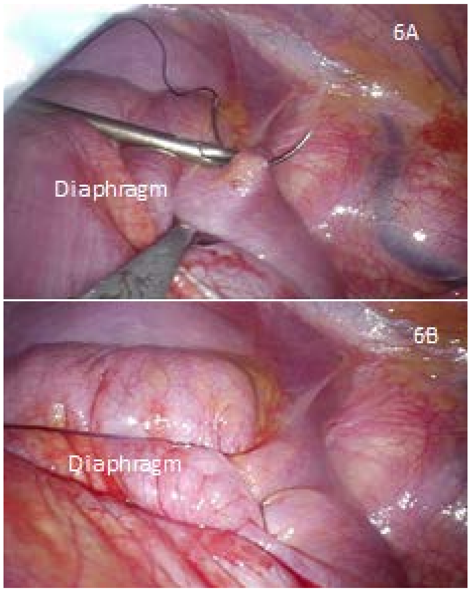


Figure 5. *VATS working portal shown anteriorly with wound protector in place. Second thoracoscopic working portal with trochar in place anteroinferiorly. Incisions for thoracic vertebra dictated by CT guidance trajectory. Posterior incision for CT reference frame.*

placed over the upper thorax out of the surgical field. The patient is widely prepped and draped to leave the thoracolumbar spine and lateral torso from axilla to iliac crest exposed. Surgeons are positioned both anterior and posterior to the patient with associated video monitors placed for viewing thoracoscopy and CT-guided navigation (Figure 3 and 4). Total intravenous anesthesia without muscle relaxation is utilized for the purpose of monitoring MEPs. Double lumen intubation is used to deflate the ipsilateral lung, which provides adequate exposure for instrumentation of the thoracic and L1 vertebral bodies. In our experience, carbon dioxide insufflation is not required for visualization. Selective



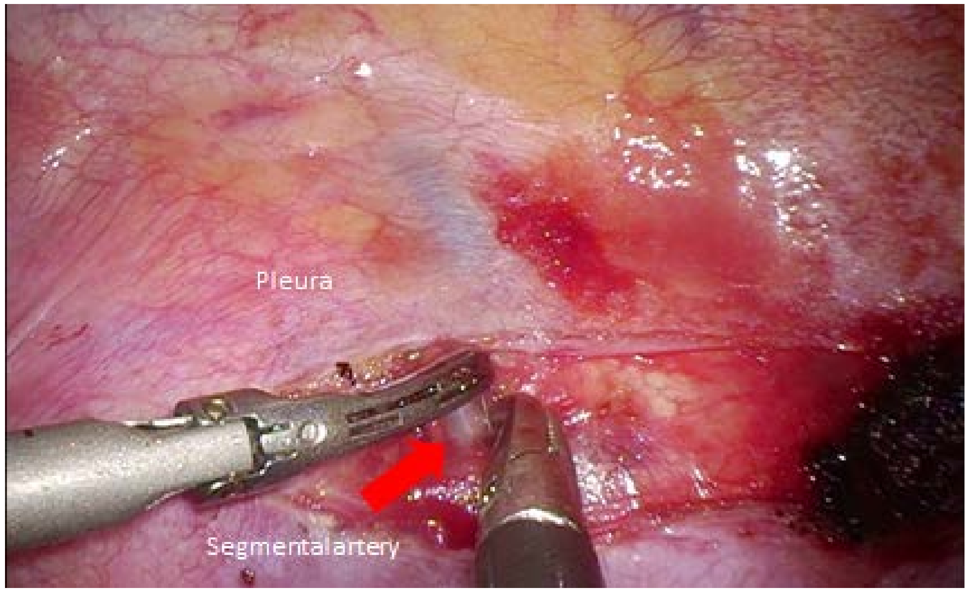


Figure 6 A and B (left). *The diaphragm is retracted by placing a figure-of-eight stitch in the muscular portion of the diaphragm and pulling anteroinferiorly to expose the T10-L1 vertebral bodies.*
Figure 7 (right). *Exposure of the lateral vertebral body and ligation of segmental vertebral arteries.*

lung ventilation is more practical to maintain thoracoscopic exposure of the spine as compared to a pressurized pneumothorax due to the need for open portals for screw and tether placement.

Thoracoscopy-Assisted Anterior Vertebral Body Tether

Thoracoscopic exposure is provided through two anterior portals. After deflating the ipsilateral lung, a 2-cm incision is made anterior and slightly inferior to the scapular tip for the initial VATS working port (Figure 5). The latissimus dorsi muscle is retracted posteriorly, and the serratus anterior and intercostal muscles are split. A wound protector (XX-small Alexis Wound Protector, Applied Medical, Rancho Santa Margarita, CA) is placed. A second 5-mm working port is placed under thoracoscopic visualization low in the chest to allow access to T12 and L1 vertebral bodies (Figure 5). The diaphragm is retracted by placing a figure-of-eight stitch in the muscular portion of the diaphragm and pulling anteroinferiorly to expose the T10-L1 vertebral bodies (Figure 6A and 6B). Extensive dissection should be avoided to prevent disruption of the lymphatics. In the thoracic spine, the 1 cm area of exposure is just

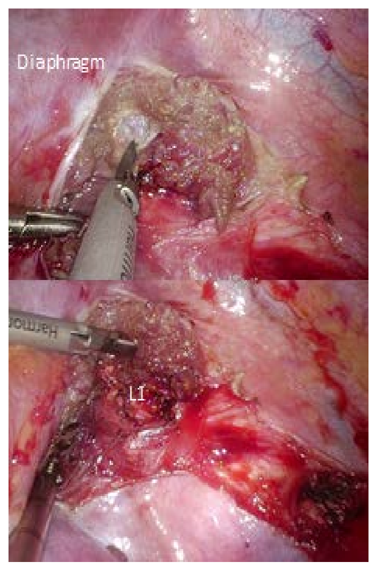


Figure 8. *Opening of posteromedial diaphragm to expose L1.*

anterior to the rib heads at the level of the segmental vessels. At L1, navigation can be used to determine the correct anterior-posterior exposure as there is no rib head for localization. A 1-cm exposure in the pleura is then opened over the lateral surface of the anticipated instrumented vertebral bodies, and segmental arteries are ligated with ultrasonic shears (Ethicon Endo-Surgery, Cincinnati, OH) (Figure 7). Neuromonitoring is critical for detecting spinal cord ischemia at this

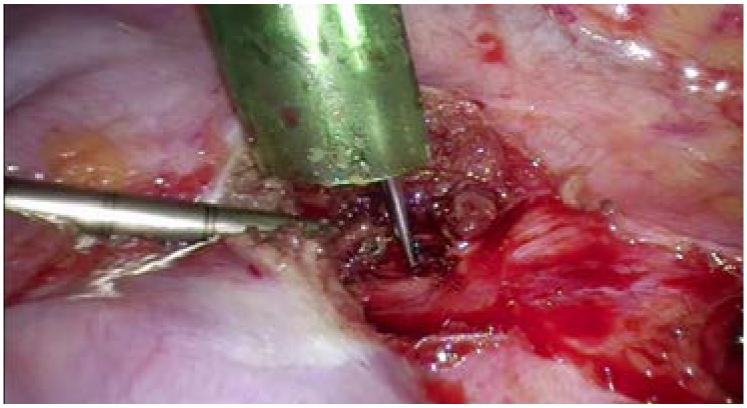


Figure 9. *CT guidance of AVBT screw placement. (A) CT guided probe selects trajectory.*

time. The posteromedial muscular diaphragm is then opened to expose L1 (Figure 8). Instrumentation of the spine proceeds through 1 to 3 posterior 15-mm portals. In general, these portal incisions are placed over the rib so that two to three spinal levels can be instrumented (above and below the associated rib) through each skin incision. Typically for instrumented vertebrae T10–L1, we can utilize the thoracic portal at the T11 level to place the T10 and T11 screws. Care should be taken placing the L1 portal through the fascia below the T12 rib with thoracoscopic visualization of the trocar as it enters the chest to ensure it is not damaging any retroperitoneal structures.

Once the thoracic vertebrae are exposed, attention is turned to placing the reference frame for CT-guidance. A longitudinal incision is made over the apical spinous process (Figure 5). This spinous process is exposed subperiosteally with care to preserve the interspinous ligament. A reference frame clamp is placed, and an intraoperative CT scan is completed for navigation purposes. This CT scan is obtained on lowest pediatric dosing to minimize exposure to radiation, typically 70 kV/16 mA/64 mAs for patients < 60 kgs and 80 kV/20mA/80 KV for patients more than 60 kgs.[18] Navigation technology is used to identify the best skin incision, entry site, and trajectory for screw placement at each level (Figure 5). A trajectory is selected midline in the sagittal plane and mid axial to match rotation of the

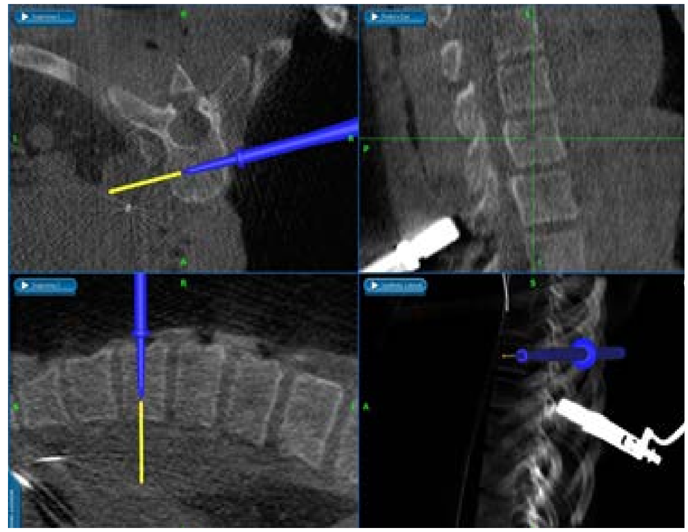


Figure 9. *CT guidance of AVBT screw placement. (B) Intraoperative CT navigation views.*

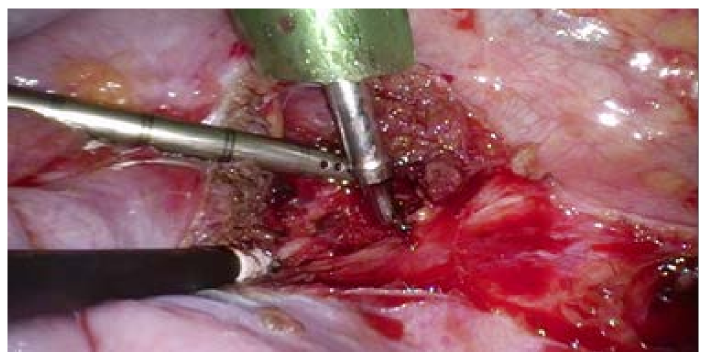


Figure 9. *CT guidance of AVBT screw placement. (C) Awl prepares trajectory.*

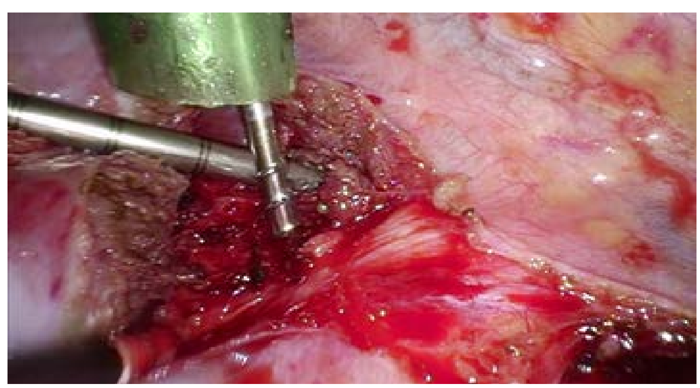


Figure 9. *CT guidance of AVBT screw placement. (D) First tap makes preliminary trajectory through to penetrate far cortex*

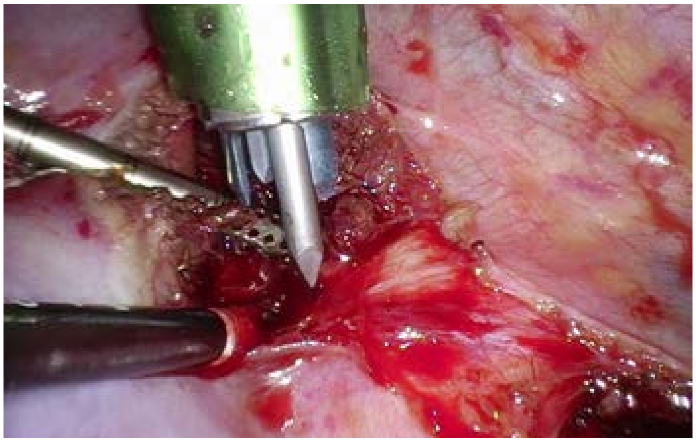


Figure 9. *CT guidance of AVBT screw placement. (E) Staple is placed.*

vertebrae (Figure 9 A-H). A navigated awl is used to prepare the screw placement. A navigated tap is used to tap the entire length of screw placement including, critically, the distal cortex. A ball-tipped probe is then used to confirm four intact walls, and a breached far lateral cortex and to correspondingly demonstrate the vertebral canal has not been entered. The screw trajectory is measured. Typically, 4 mm is added to the measured bone-to-bone length to accommodate length for the staple and ensure bicortical fixation. A staple is placed around the tapped hole to provide additional stability and consistent screw placement depth. The path is tapped again with a larger tap sized for the planned screw, and the hydroxyapatite-coated screw is placed. The process is repeated for all intended instrumented thoracic vertebrae as well as L1.

Lumbar Anterior Vertebral Body Tether

Attention is then turned to the lumbar spine. Access to L2-L4 is through an oblique 4-6 cm incision over the lateral flank (Figure 10). Dissection is carried through the external oblique, internal oblique, and transversalis abdominis muscles to the retroperitoneum. The psoas muscle is identified, and the peritoneum is bluntly dissected anteriorly to reveal the psoas muscle from the level of the diaphragm to the desired level. Minimally invasive techniques using electromyography (EMG) probes and sequential dilators to identify the lumbar

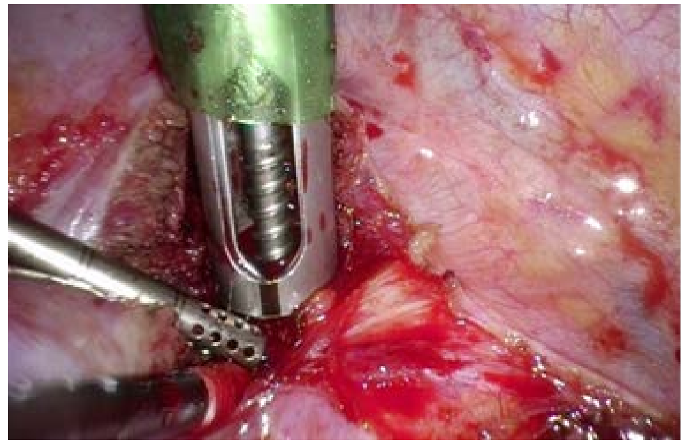


Figure 9. *CT guidance of AVBT screw placement. (F) Final tap for appropriate screw size.*

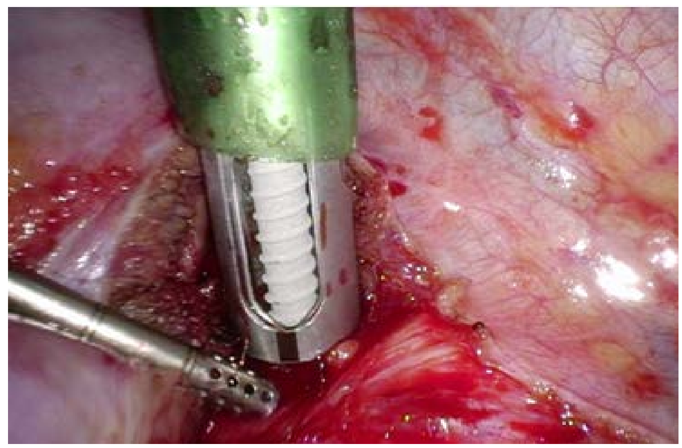


Figure 9. *CT guidance of AVBT screw placement. (G) Screw placement.*

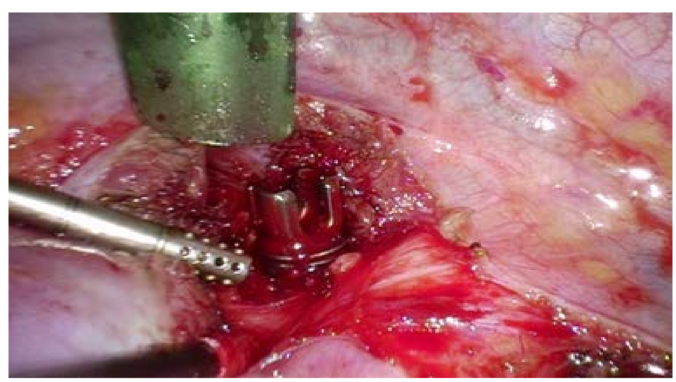


Figure 9. *CT guidance of AVBT screw placement. (H) Final screw position.*

Figure 10 (left). *Oblique flank incision.* ***Figure 11 (middle).*** *Trans-psoas view of screw placement.* ***Figure 12 (right).*** *Lumbar vertebral tethering. (A) Screw-tether interface outside of body.*

plexus and progressively distend psoas musculature away from the intended screw trajectories may also be applied. Stimulation of the adjacent musculature with an EMG probe should be performed to ensure that the lumbosacral plexus is not adjacent to the area of planned screw placement. Alternatively, the psoas muscle may be bluntly retracted posteriorly off the vertebral bodies to expose the lateral vertebral surface. Multiple long narrow retractors are needed to provide adequate visualization again to ensure that the starting point of the screw is clear from the lumbosacral nerves. Once an unobstructed and safe path to lumbar vertebrae has been established, segmental arteries are again divided using electrocautery or ultrasonic shears (Ethicon Endo-Surgery, Cincinnati, OH). An awl is used to prepare the screw entry site and the full trajectory is preliminarily tapped, checked for four intact walls, measured for length, the staple placed, and final trajectory re-tapped for the desired screw. A 6-mm hydroxyapatite-coated titanium screw is then placed. The process is repeated for the remaining lumbar vertebra (Figure 11). Typically, the L2 and L3 screws can be placed through the same incision. A second incision and retroperitoneal approach are sometimes required for the L4 screw. It is important to frequently verify accuracy of the navigated instruments by checking the image against known anatomic landmarks. Live fluoroscopy can be used in place of navigation, but care should be taken to obtain a true orthogonal biplanar view of each vertebral body to ensure safe trajectory and screw length. Once all the screws are placed and neuromonitoring checks have been performed, intraoperative navigation can be discontinued.

Our workflow includes tensioning of the distal instrumented levels first. One end of the cord is cut since tensioning is performed caudad to cephalad. Tensioning is performed as needed to achieve the anticipated postoperative correction. The lumbar spine is more flexible than the thoracic spine, and over tensioning should be avoided. Maximal tensioning is applied at the apical vertebral levels. The cord is placed in the most distal screw, and the set screw is applied (Figure 12A-C). The reduction tower is then placed on the next most distal screw. At this point, the table is bent from an extended position into a flexed position typically of 10 degrees to facilitate the reduction (Figure 13A and B). Once the table is flexed, there is less space available to work, and it is more difficult to obtain an orthogonal trajectory down to the screw heads for placement of set

Figure 12. *Lumbar vertebral tethering. (B) Tether cord placed in lumbar screw.*

Figure 12. *Lumbar vertebral tethering. (C) Lumbar tether tensioning in situ.*

screws. Sequential tensioning is then carried out as indicated based on curve magnitude, flexibility, and growth remaining. Care should be taken not to damage the cord during the tensioning process. For a transpsoas approach, care is taken not to overly compress the psoas muscle under the cord.

Once the L2 set screw is placed, the next step is to pass the cord from the retroperitoneal space into the chest. A retractor is placed superiorly in the abdominal wound to expose the undersurface of the diaphragm. Typically, placement of the L1 screw results in a small window in the diaphragm. The thoracoscope is placed in the chest for visualization, and then the L1 screw is manually palpated from the retroperitoneal incision and is usually readily felt. Then a large, blunt hemostat can be used to pass the cord from the retroperitoneal incision safely up into the chest under thoracoscopic visualization (Figure 14). Tensioning is then carried out through the thoracoscopic approach according to the preoperative plan. Less tension is typically applied at the most proximal disc space to avoid excessive loading of the most proximal screw. The table is then placed in a flat position, and an intraoperative radiograph can be obtained at this time to evaluate curve correction and whether further adjustment of the tether tension is necessary. When curvature and tension are deemed appropriate, set screws are finally tightened, and the excess proximal cord is trimmed. A final neuromonitoring assessment is completed. Prior to closure, the opening in the diaphragm is closed thoracoscopically, a chest drain is placed through the lower thoracoscopic portal, and the collapsed lung is ventilated under direct visualization. The retroperitoneal exposure and thoracic portals are closed in layers. A postoperative chest radiograph is obtained for monitoring of pneumothorax. The procedure duration is 3-4 hours.

Postoperative Course

Drain output is monitored daily, and a chest x-ray is taken after the chest tube is removed. Mobilization is expected on postoperative day one. Pain control is managed with an intrathecal injection of hydromorphone and a paravertebral pain catheter. This is transitioned to oral pain control as tolerated. Discharge typically occurs by postoperative day three. Patients are advised to avoid sports or other high-intensity activities for 6-weeks postoperatively to allow for ingrowth of the vertebral

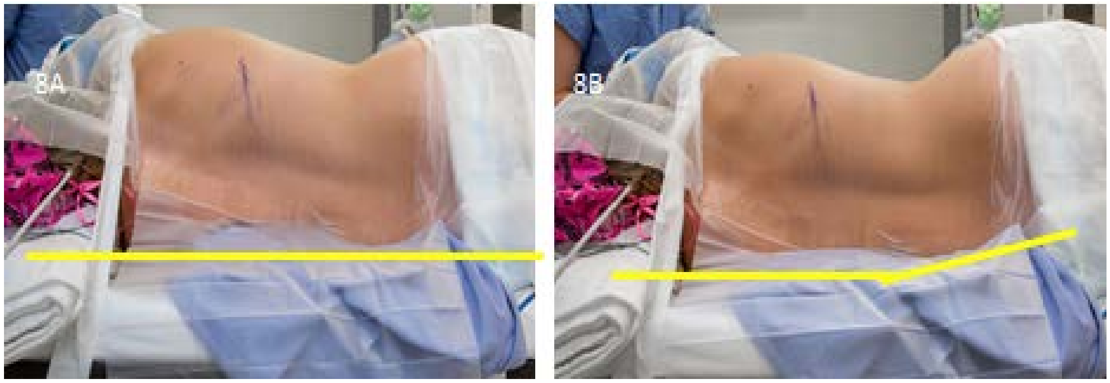


Figure 13. *Flexed-bed assistance with curve reduction. (A) Patient side lying on the table normally. (B) Patient with 10 degrees of flexion through the curve to assist with reduction.*

screws. Clinically and radiographic follow-up is scheduled for every 6 months until skeletal maturity (Figure 15A-D).

Comparison to Other Methods

As previously discussed, AVBT is intended for patients with AIS who have curve magnitude in a surgical range but have remaining growth potential and desire to maintain spinal motion. In 2020, Newton et al. retrospectively compared 23 AVBT patients to a matched cohort of 26 PSF patients.[19] AVBT patients' curve magnitude ranged 40-67 degrees, age 9-15 years, Risser stage <2 with mean follow up 3.4 years. At final follow-up, AVBT patients had greater residual deformity compared to the PSF patients (mean 33 degrees vs. 16 degrees, P <0.001). There were seven patients (30%) who underwent nine revision procedures in the AVBT cohort, including three revisions to PSF, compared to no reoperations in the PSF cohort. However, patient-reported outcomes at final follow-up were similar between both groups. At this time, PSF remains a more reliable procedure for deformity correction, but curve correction and avoidance of a fusion procedure was achieved in 74% of AVBT patients in this study.

Summary

AIS is the most common spine deformity seen in children. With the recent FDA humanitarian device approval for the Tether System (Zimmer Biomet, Warsaw, IN), there will be an increased utilization of the procedure in the U.S. Similar devices have been

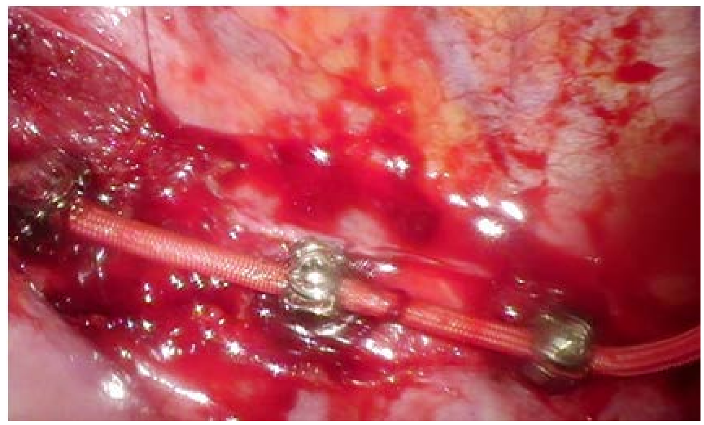


Figure 14. *Thoracoscopic view of trans-diaphragm linked tethers.*

approved in Europe under a CE mark (Reflect, Globus Medical, Audobon, PA; and Braive, Medtronic, Minneapolis, MN). AIS commonly affects the lumbar spine, but to date, there are limited published techniques for anterior body tethering of the lumbar spine. Thus, our group sought to provide information regarding lumbar anterior vertebral body tethering so as to disseminate best practices as this procedure gains widespread application.

Posterior spinal fusion is a widely utilized surgical technique for treatment of severe AIS. Adequate results are obtained with posterior spinal fusion with reoperation rates between 4-25% at long-term follow-up.[5,20-22] Modern fusion approaches provide excellent and durable curve correction but limit spinal motion over the instrumented vertebrae and sacrifice normal spinal anatomy. Associated risks include neurologic injury, pseudarthrosis, adjacent segment disease, and potential for revision surgery and long-term complications.

Non-fusion options for scoliosis treatment were developed to preserve spinal anatomy, maintain mobility, and were preceded by the successes of guided growth in other areas of pediatric orthopaedics. There are limited series of published short-term outcomes of anterior vertebral spinal tethering.[9-11,19] Long-term outcomes have yet to be established. There are known concerns of either over-correction or under-correction of the spinal curve, progression of the scoliosis despite tethering, screw migration, significance of tether breakage, neurologic injury, and vascular injury to the great vessels. With regard to undercorrection, overcorrection, or curve progression, treatment options include revision tether surgery or posterior spinal fusion. The pulmonary consequences of revision tether surgery are unknown, and the presence of scar tissue in the thoracic cavity and retroperitoneum can present significant challenges. The significance of tether breakage also remains debated.[10,19] Fortunately, spinal fusion after an attempt at non-fusion surgery remains a viable option. Further studies reporting long-term outcomes are needed to answer these questions regarding growth modulation. Clearly, anterior vertebral body tethering will undergo continued optimization as it is applied, with potentially lower revision rates as the technique evolves.

This article aims to improve the safety of lumbar anterior vertebral body tethering by providing a detailed description of the technique. A successful procedure requires familiarity with the thoracic and retroperitoneal anatomy, adequate intraoperative imaging via navigation or fluoroscopy, and careful preoperative planning to achieve the desired tether tension.

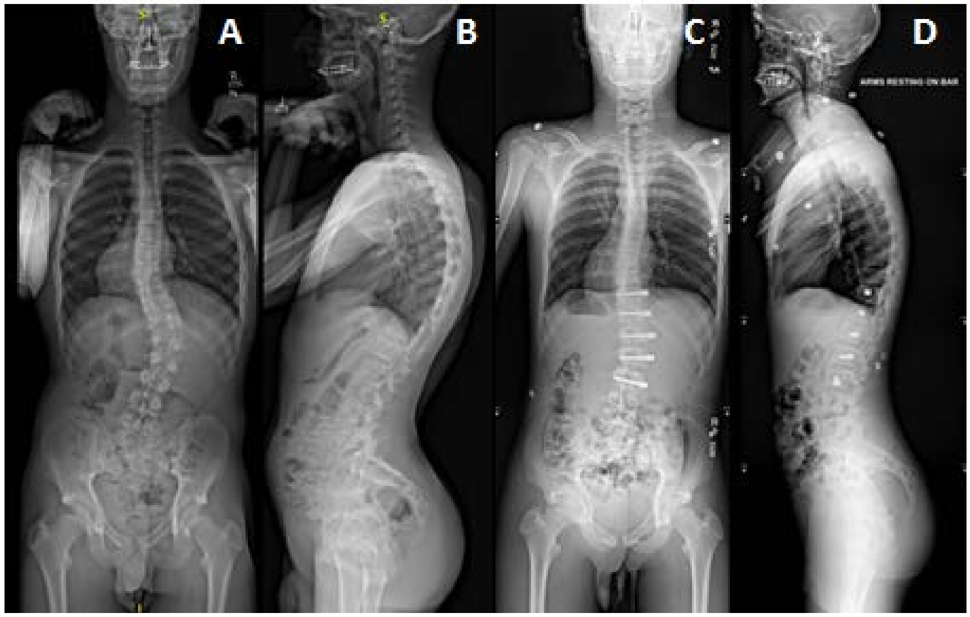


Figure 15. *(A, B) AP and lateral pre- and (C, D) AP and lateral postoperative radiographs. Full length scoliosis views demonstrating lumbar curve reduction after placement of anterior lumbar vertebral body tether.*

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