Adolescent Scoliosis

37

Daniel J. Miller, Todd J. Blumberg, Susan E. Nelson, Per D. Trobisch, and Patrick J. Cahill

Learning Objectives
By the end of the chapter, readers should be able to recall:

- Techniques and outcomes for less invasive posterior spinal fusion
- The utility of thoracoscopic release in spinal fusion
- Principles of spinal growth modulation
- Indications and outcomes for vertebral body stapling and tethering techniques

37.1 Introduction

The conventional approach to the scoliotic spine involves a midline skin incision followed by a midline fascial incision and wide subperiosteal muscle stripping of the paraspinal musculature laterally to the tips of the transverse processes. This exposure facilitates identifying anatomic landmarks for screw or anchor insertion and facilitates preparation of posterior bony surfaces and facet joints for fusion.

D. J. Miller
Department of Orthopaedic Surgery, Gillette Children's Specialty Healthcare, St. Paul, MN, USA

T. J. Blumberg
Department of Orthopaedics and Sports Medicine, University of Washington/Seattle Children's Hospital, Seattle, WA, USA

S. E. Nelson
Department of Orthopaedic Surgery, Children's Hospital of Philadelphia, Philadelphia, PA, USA

P. D. Trobisch
Department of Spinal Surgery, Eifelklinik St. Brigida, Simmerath, Germany

P. J. Cahill (✉)
Division of Orthopaedic Surgery, The Children's Hospital of Philadelphia, Philadelphia, PA, USA
e-mail: cahillp1@email.chop.edu

Unlike in degenerative spine surgery, implants are utilized not only for stability but also intraoperatively to manipulate spinal alignment. This adds an additional layer of difficulty in adopting less invasive degenerative implants and techniques to deformity applications. Nonetheless, significant success has been achieved by a small number of surgeons in performing less invasive spinal deformity surgery.

The theoretical advantages of a less invasive approach in spinal deformity surgery are similar to those in other less invasive spine surgery applications: less blood loss, less muscle disruption, decreased pain, lower infection rates, and quicker recovery. In some patients who are unable to receive a blood transfusion, such as patients who are Jehovah's Witnesses, MIS or LIS techniques make spinal deformity a more realistic option due to decreased average surgical blood loss when compared to traditional open spinal fusion.

Although most spinal deformity surgeons prefer to access the spine posteriorly, the anterior approach has several advantages. Thoracoscopic technique for scoliosis surgery allows for minimally invasive access to the thoracic spine for anterior release or for instrumentation and fusion. As such, the thoracoscopic approach is a valuable tool in the deformity surgeon's armamentarium.

There is a growing body of literature and experience in the fusion-less treatment of spinal deformity. The MIS principle of preservation of muscles, discs, and other soft tissue structures becomes even more critical in these patients for whom motion preservation is a goal. Almost all of these fusion-less techniques utilize the principles of less invasive surgery.

This chapter will discuss advantages and disadvantages of various applications of less invasive techniques and implants in the treatment of adolescent spinal deformity. Since MIS techniques in pediatric spinal deformity are still in its infancy, emphasis will be placed on the authors' experience.

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Typical surgery for adolescent scoliosis involves wide exposure of bony anatomy to facilitate multi-segmental instrumentation.

37.2 Fusion Procedures

37.2.1 Posterior

While true percutaneous posterior spinal instrumentation and fusion (PSIF) through multiple stab incisions is technically feasible, this technique has not gained wide acceptance due to inferior cosmetic outcome compared to a single long midline incision. As such, the majority of posterior MIS or LIS spine techniques for scoliosis are currently performed through one to three long midline skin incisions combined with some type of Wiltse-like muscle splitting approach (Table 37.1).

One of the most significant concerns that has prevented widespread adoption of LIS techniques in scoliosis surgery is apprehension regarding the ability to obtain bony fusion. Open techniques allow for meticulous preparation of the fusion bed under direct visualization whereas LIS techniques are often under radiographic guidance through small access points. Obtaining a solid fusion is less of a concern in children, as the pediatric spine often fuses unintentionally solely as a result of muscle disruption during spine exposure and/or secondary to prolonged instrumentation [1]. Critics also cite the inability to place copious amounts of bone graft at the fusion bed as a major shortcoming of MIS; however, the importance of bone grafting in pediatric spinal fusion has been questioned. Betz et al. [2] reported a prospective, randomized trial of patients with acute ischemic stroke (AIS) undergoing a posterior fusion and reported no cases of pseudarthrosis in patients who received no bone graft (the local autograft being discarded). It can be hypothesized, however, that the subperiosteal exposure that was used for both groups significantly contributed to osseous fusion.

Table 37.1 Less invasive posterior spinal fusion for scoliosis: comparison of techniques and perioperative outcomes from various series

Series	Technique	EBL (cc)	Surgical time (minutes)	Length of hospitalization (days)
Newton et al. [62]	Thoracoscopic	470	344	6
Wimmer and Pfandlsteiner [3]	Concave open, convex Transmuscular	165	175	Not reported
Durrani et al. [4]	Transmuscular	261	297	3
Miyanji et al. [5]	Wiltse	277	444	4.6
Sarwahi et al. [6]	Transmuscular	600	539	8
Zhu et al. [7]	Wiltse	153	252	Not reported

Wimmer and Pfandlsteiner [3] reported results of a hybrid approach to scoliosis surgery that included both traditional and LIS techniques for instrumentation and fusion. Patients had a conventional open exposure and instrumentation on the concave side of deformity using up to three midline skin incisions. Once the rod was seated on the concave side and correction was achieved, transmuscular screw and rod instrumentation was performed on the convex side with the use of dilatators and fluoroscopic assistance (Fig. 37.1). Their series included 49 patients with neuromuscular or idiopathic scoliosis (age 16–29 years). The authors reported an average surgical time of 175 min, an estimated blood loss (EBL) of 165 mL, and an average coronal curve correction of 75%. An average of 2° of correction was lost at 27 months and 5% of patients failed to fuse. There were no instances of infection and no neurologic complications.

Durrani et al. [4] reported on a transmuscular technique used in 30 pediatric patients with a variety of diagnoses. Three skin incisions were used in the technique placed over the proximal and distal ends of the planned construct, and at the apex of the deformity. The pedicles were instrumented over guidewires placed through Jamshidi needles, inserted through the muscle under fluoroscopic guidance. This technique resulted in shorter skin incisions but precluded the use of bilateral guidewires, reduction tabs, or derotation devices at all levels at the same time. In their series, the average blood loss was 261.5 cc and the average duration of surgery was 4 h and 57 min. The average length of hospitalization was 3 days. Postoperative CT scans obtained at 6 months

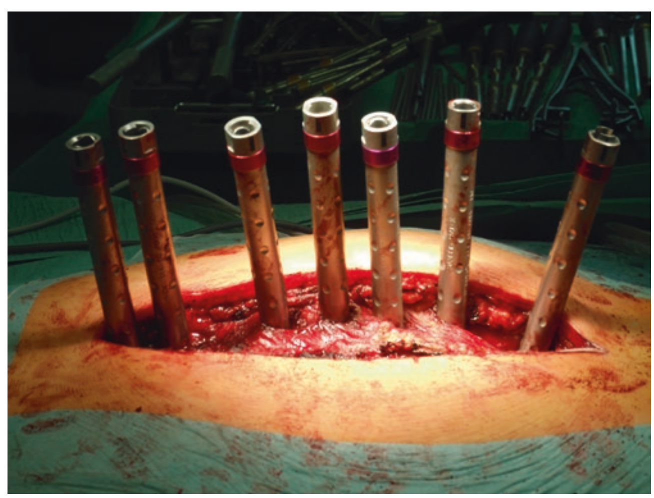

Fig. 37.1 Hybrid open/MIS technique: after instrumentation and correction via an open procedure on one side (not visible in this image), transmuscular tubes are placed for screw and rod insertion on the opposite side. (Photo courtesy of Prof. Dr. Cornelius Wimmer, Schön Klinik Vogtareuth, Germany)

post-op showed robust fusion in all patients with no evidence pseudarthrosis. Long-term follow-up of these patients has not been reported.

Miyanji et al. [5] advocate the use of three longitudinal midline skin incisions with a bilateral Wiltse approach to the transverse processes and lateral facets. In a prospective comparison with open techniques, they showed longer operative times with the MIS approach (444 min vs 350 min, 95% CI 34.8—154.0) but lower blood loss (277 mL vs 388 mL, 95% CI −207.8—(−14.1)) and length of hospitalization (4.6 days vs 6.2 days, 95% CI −2.6—(−0.6)).

Sarwahi et al. [6] presented a retrospective comparison of 15 standard PSIF cases and 7 MIS procedures utilizing 3 short longitudinal midline skin incisions and transmuscular pedicle screw placement under radiographic guidance. Pedicle screw accuracy was confirmed by CT scan. They found no difference in pedicle screw accuracy or in curve correction. MIS patients had significantly lower transfusion rates, shorter levels of fusion, and fewer pedicle screws placed. Time to mobilization, length of stay, pain scores, and patient-controlled analgesia use were similar in both groups. There were no pseudoarthroses in either group.

Zhu et al. [7] recently presented their results of 15 MIS spinal fusion cases performed with intraoperative 3D navigation for Lenke type 5C curves and compared these to traditional open PSIF technique. Their technique involved two 3–5 cm midline skin incisions, exposure of facet joints through a Wiltse approach, and placement of screws with 3D intraoperative images and a surgical navigation system. MIS patients had significantly less EBL and longer operation times compared to the open group. Interestingly, MIS patients had significantly higher patient-reported outcomes as measured by the SRS-22 at final follow-up. No differences between the groups were seen with respect to screw placement accuracy, fusion rate, or radiographic measurements.

These promising less invasive techniques are possible with newer and stiffer metallurgy like cobalt-chrome. If long-term studies can confirm these short-term results, this hybrid technique may have the potential to represent an additional alternative to traditional bilateral open procedures, at least for flexible curves that would not require wide releases or posterior single-column osteotomies. A major downside of all MIS techniques is the longer radiation time and the direct effect on the patient and the surgeon. Future research must focus on less radiation dosage fluoroscopy, low-radiation navigation, and/or a freehand pedicle screw insertion technique for MIS procedures.

> Less invasive posterior spinal fusion for adolescent scoliosis is possible through transmuscular instrumentation.

37.2.1.1 Authors' Preferred Technique

In contrast to the authors of the previously discussed series, the authors of this chapter prefer to use a single skin incision (Fig. 37.2a) that precludes the need to mobilize the skin to access various levels at different times, thus allowing all inserters to remain in place bilaterally throughout the case. In our experience, this allows for better direct vertebral body derotation. The skin is incised in the midline but the fascia remains intact. Under anteroposterior (AP) fluoroscopic guidance, the pedicles are entered transmuscularly with a Jamshidi needle (Fig. 37.2b). The stylette is removed and a guidewire is inserted and advanced, preferably under lateral fluoroscopic guidance. Once all bilateral guidewires are in place, the pedicles are tapped with a cannulated tap (Fig. 37.2c). Prior to placing the screws, a small nasal speculum is used to access the facet joint to allow decortication with a high-speed burr (Fig. 37.2d). A cannulated screw (Viper System, DePuy Spine, Inc., Raynham, MA) with an extended slotted inserter is placed over the guidewire. The Viper System is used because of the longitudinal slot which facilitates the spine correction maneuvers. The tapping and screw insertion should be performed under lateral image intensification to ensure that the guidewire is not advanced while the threads are advancing. Once the screw is in place, the guidewire is removed but the extended inserter is left affixed to the screw. At this point, the reduction is performed as described by Rodriguez-Olaverri et al. [8]. Two straight rods are placed into the slotted inserters on the convex side of the spine dorsal to the skin. The rods are then pulled as far apart as possible within the screw inserters, thereby reducing the scoliosis curvature (Fig. 37.2e). With the spine held in this position, the concave rod is passed submuscularly. If screws are placed at each level, passing the rod is relatively uncomplicated. The rod should be precontoured to the desired sagittal alignment. The rod is secured with set screws. The spinal alignment may be further adjusted through compression and distraction between the screw extensions. The two convex temporary rods are removed. Direct vertebral rotation maneuvers are performed at this stage in a manner similar to open procedures. Next, a submuscular rod is passed on the convex side. The fusion bed is prepared bilaterally with a hemicylindrical rasp with curved handle that is passed submuscularly along the spinous processes and lamina. Bone grafting is performed by passing a tube of mesh-encased bone graft (MagniFuse, Medtronic, Memphis, TN) along the spinous processes with a vaginal packing forceps.

Our postoperative pain management protocol includes regularly scheduled muscle relaxants at doses higher than typically used for open procedures; the less invasive technique involves dilation in the muscle belly and results in muscle pulling and stretching rather than the traditional more destructive method of detachment of muscles from their spinal origins and insertions.

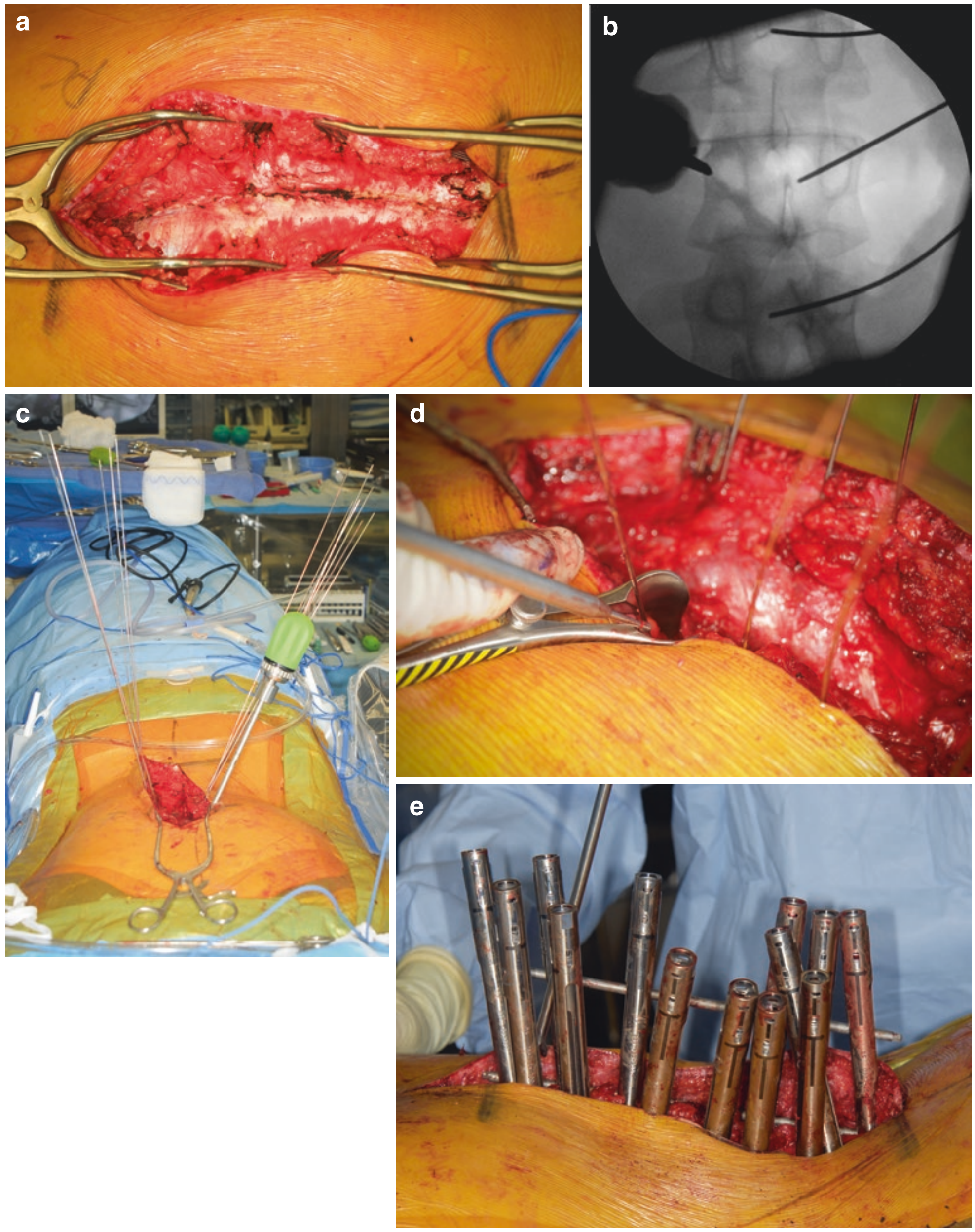

Fig. 37.2 The authors' preferred technique for minimally invasive posterior spinal fusion. (**a**) Midline skin incision with preserved muscle attachments; (**b**) fluoroscopy view of pedicle targeting; (**c**) guidewires in position and a cannulated tap utilized to prepare pedicles for screw placement; (**d**) use of nasal speculum to access facet joint for bone graft bed preparation; and (**e**) two-rod Piza-Vallespir reduction technique

37.2.1.2 Case Example

The following case demonstrates the utility of this technique. The patient is a 19-year-old overweight male with Asperger's syndrome and progressive scoliosis. He is also a Jehovah's Witness and as such he and his family would not accept a blood transfusion. He has a left thoracic and right thoracolumbar prominence measuring 10° and 20°, respectively, on Adams' forward bend test. His right shoulder is elevated 3 cm. He has no neurologic deficits in his lower extremities. Preoperative imaging revealed a 60° thoracolumbar curve that reduced to 44° on side bending and a 40° thoracic curve that reduced to 25° (Fig. 37.3a). After appropriate preoperative counseling, he underwent a less invasive instrumented posterior spinal fusion from T9 to L3 without complication (Fig. 37.3b).

37.2.2 Anterior

In contrast to posterior surgery, anterior surgery can in fact be performed with a true MIS approach. This usually requires only three or four half-inch skin incisions that will be used as thoracoscopic working portals or a mini-open lumbar retroperitoneal approach.

Dwyer et al. [9] in 1969 initially described the anterior approach to the scoliotic spine, and only a few years later, Zielke et al. [10] published the results of 26 patients who underwent an instrumented ventral derotation spondylodesis. It is therefore somewhat surprising that despite the feasibility and theoretical superiority of thoracoscopic surgery over conventional thoracotomy, it took almost three decades for the first papers to be published on thoraco-

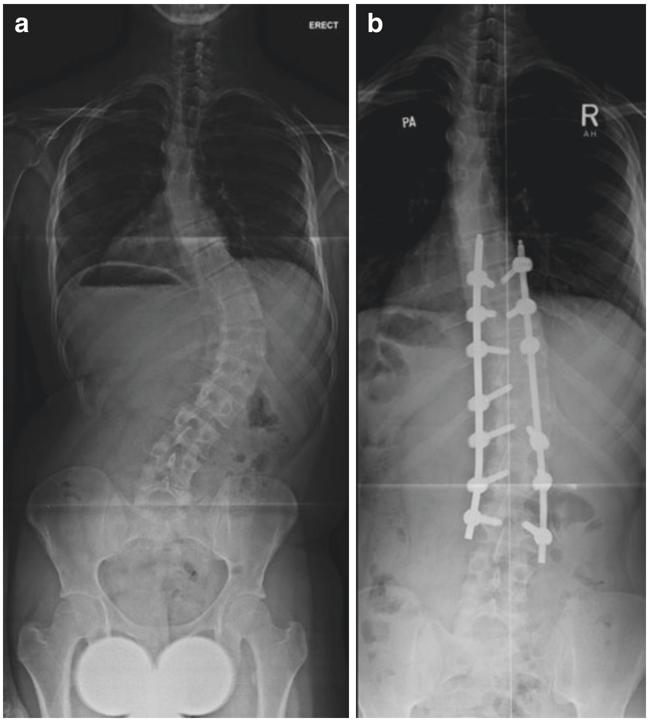

Fig. 37.3 Case example of less invasive posterior spinal fusion. (**a**) Standing preoperative PA demonstrating a thoracolumbar scoliosis. (**b**) Standing postoperative PA revealing correction of the deformity and excellent overall alignment

scopic scoliosis surgery. Anterior scoliosis surgery broadly encompasses any anterior discectomy (release) with or without instrumentation.

37.2.2.1 Anterior Release

Traditionally, the most popular surgical procedure for thoracic scoliotic curves exceeding 80° was open anterior release followed by posterior spinal instrumented fusion. Due to the high morbidity of thoracotomy, the more powerful correction forces of newer posterior instrumentation, and the increasing popularity of posterior osteotomies, anterior releases have fallen out of favor. However, video-assisted thoracoscopic surgery (VATS) made minimally invasive anterior releases feasible.

Longis et al. [11] reported radiographic outcomes of patients with idiopathic scoliosis who were treated with PSIF alone ($n = 15$) compared to those treated with video-assisted thoracoscopic release in addition to PSIF ($n = 14$). Thoracoscopy was not associated with improved short-term results in terms of Cobb angle or spinal balance. Thoracoscopic release was associated with a significantly improved correction of thoracic hyperkyphosis, with an additional correction of 15° observed in this group.

Anterior thoracoscopic releases can also be performed in the prone position (Fig. 37.4). Prone thoracoscopic anterior release provides two significant advantages over open or thoracoscopic anterior release performed in the lateral decubitus

Fig. 37.4 Picture showing portal location and feasibility of prone thoracoscopic anterior release. (Photo courtesy of Daniel J. Sucato, MD)

position: (1) posterior surgery can be performed under a single prep and drape, avoiding transition time between the two positions, and (2) ipsilateral lung deflation and single lung ventilation are not required due to the effect of gravity pulling the lung anterior [12]. In 2000, King et al. [13] reported on a series of 27 pediatric cases in which they performed concomitant prone thoracoscopic anterior releases in addition to posterior fusion. The anterior procedure released an average of 3.3 discs and took an average of 129 min. Also, in 2000, Böhm and El Saghir [14] published their results of 60 patients with either idiopathic or neuromuscular scoliosis with a mean age of 19 years (range 8–56) at surgery. On average, 3.4 segments were mobilized via anterior thoracoscopic release in the prone position. The average preoperative Cobb angle of 72° (range 44–121) was corrected to 18° (range −3 to 39) postoperatively. In addition, all patients with hypokyphosis could be corrected. The average axial correction was 80%. There were no neurologic deficits or wound infections. Two patients required revision surgery, one because of a hemothorax and another due to a misplaced pedicle screw.

Sucato et al. [15] presented their data of 13 patients who had thoracoscopic anterior release in the prone position followed by posterior spinal fusion and instrumentation (TAR-PSFI) compared to 83 patients without anterior release prior to posterior spinal fusion and instrumentation (PSFI). Patients with TAR-PSFI were observed to have a more rapid decline of pulmonary function in the first 3 weeks postoperatively but recovered significantly and were better compared to patients with PSFI at 1-year follow-up. If a thoracoplasty was added to the procedure, postoperative pulmonary function was equivalent irrespective of whether or not TAR was performed [14]. When Sucato and Elerson reviewed outcomes of patients who underwent prone ($n = 16$) versus lateral (n = 27) thoracoscopic anterior release, patients in the prone group had less delay between the anterior and posterior procedures, no complications related to single lung ventilation, required less postoperative oxygen support, and were discharged home earlier [12].

37.2.2.2 Anterior Instrumentation and Fusion

Anterior spinal fusion for the treatment of scoliosis avoids the painful and destructive effects of posterior muscular detachment, offers comparable curve correction, and may save fusion levels. Betz et al. [16] published a retrospective comparative study of matched AIS patients treated with anterior or posterior spinal fusions. They found that anterior fusions had equivalent correction of the Cobb angle in the coronal plane and more improvement in the thoracic hypokyphosis. Furthermore, the anterior fusions were an average of 2.5 levels shorter than the posterior fusions [16]. Anterior scoliosis surgery became even less invasive with the advent of thoracoscopic anterior fusions. In 2001, Picetti et al. [17] reported their results of 50 patients who were treated with thoracoscopic instrumented spinal fusion for scoliosis. Wong et al. [18] published their results of patients undergoing VATS compared to patients who received posterior all-hook instrumentation and fusion. In 31 patients with AIS that were followed up for an average of 44 months, VATS was found to decrease blood loss but increase surgical time and ICU days. No differences were found with respect to analgesic requirement or hospital stay. There were no complications in the PSF group and two in the VATS group; one patient had a prolonged pneumothorax and the second patient suffered injury to the long thoracic nerve resulting in scapular winging. Coronal curve correction at final follow-up was 67% for patients with PSF and 62% for patients with VATS. However, this difference was not found to be significant. Both groups were found to have a loss of correction over time. No differences were identified with respect to sagittal curve behavior postoperatively. Notably, VATS patients were required to wear a hard brace for 3 months postoperatively. On the other hand, anterior instrumentation was able to save an average of 3.5 fused segments.

Lonner et al. [19] compared the results of pulmonary function tests at a minimum follow-up of 24 months after various anterior stand-alone procedures in 131 patients with AIS. Sixty-eight patients had an open thoracotomy and forty-four patients had a video-assisted thoracoscopic instrumentation for Lenke type 1 curvature (single thoracic curve). In addition, 19 patients had thoracoabdominal surgery for a Lenke type 5 curvature (lumbar/thoracolumbar curve). Significantly, better pulmonary function was found in favor of the thoracoscopic group. The open thoracotomy group experienced significant declines from preoperative to 2 years postoperative in mean absolute forced expiratory volume in 1 s (FEV1) and forced vital capacity (FVC). In contrast, the thoracoscopic group demonstrated either slight or statistically significant improvements in mean absolute FEV1, FVC, and total lung capacity (TLC). No differences with respect to FEV1, FVC, or TLC were observed in patients who had thoracoabdominal surgery.

Lee et al. [20] review outcomes of 65 patients with AIS and Lenke type 1 curve patterns treated with thoracoscopic ASIF (n = 42) vs PSIF with all pedicle screw constructs (n = 23). The thoracoscopic ASIF group was associated with less intraoperative blood loss and with equivalent pain scores and satisfaction at 2-year follow-up. ASIF was associated with a significant rate of implant failure (12%) and significant pulmonary complications (7%) requiring treatment.

In summary, thoracoscopically assisted surgery in the treatment of idiopathic scoliosis is a viable alternative to conventional thoracotomy and can also be used for anterior releases as an adjunct to posterior spinal fusion of severe scoliotic curves. However, despite several advantages, thoracoscopic scoliosis surgery has still not achieved wide acceptance. This may be due to reported higher pseudarthrosis rates (4–5%), difficulty and length of time needed to perform the discectomies, and reports of anterior screws impingement on the aorta [21]. In addition, there has been significant improvement in outcomes from posterior techniques over the past 20 years with respect to blood loss, operative time, length of stay, rate of major complications, and patient-reported outcomes [22]. These recent advances in posteriorly based surgery contribute to the inability of anterior surgery, even if performed minimally invasively, to achieve gold standard status.

> Thoracoscopic anterior spinal fusion allows for minimally invasive instrumentation and fusion but is associated with a higher rate of pseudarthrosis.

37.3 Fusion-Less Treatment of Scoliosis

The previous sections of this chapter addressed less invasive methods of performing spinal fusions for the treatment of spinal deformity. While these treatments may be less disruptive to soft tissues, they still lead to the same functional limitations of decreased flexibility as open procedures. Furthermore, patients with scoliosis fusion have significant risk of reoperation for pain and degeneration due to stresses imparted to the few remaining mobile segments adjacent to a long fusion. As such, several surgeons are innovating surgical methods to control spinal deformity without fusion.

The natural history of curve progression in idiopathic scoliosis is dependent on the patient's skeletal maturity, curve pattern, and curve severity [23]. Patients with significant growth potential and large initial curves are 74% more likely to progress without treatment [24–26]. Dimeglio et al. [27] have shown that patients who have moderate size curves (30–40°) who have not had their pubertal growth spurt have an almost 100% chance of progression to 50° or more. Patients with curves between 50° and 75° at maturity, particularly thoracic curves, will progress an average of 29.4° in adulthood [28]. Therefore, prevention of curve progression beyond 50° is recommended.

The current standard of care for immature patients with AIS is a cervicothoracolumbosacral orthosis (CTLSO) or a thoracolumbosacral orthosis (TLSO). Data from the Bracing in Adolescent Idiopathic Scoliosis Trial (BRAIST) strongly support the use of TLSO bracing to control curve progression and to decrease the likelihood of surgery [29]. Despite this, 18–50% of curves that are candidates for bracing will progress in spite of brace wear [24–26, 29–34]. This number may be even higher in very skeletally immature patients. Karol et al. [35] demonstrated that 44% of patients who were Risser stage 0 at initiation of brace wear progressed to a surgical range, despite a daily brace wear over 11 hours. The percentage of patients progressing to surgery was even higher (63%) for patients with an open triradiate cartilage. With increased understanding of bracing, compliance, and skeletal maturity indices, we will be able to more reliably identify patients who have a high chance of brace failure. These patients are attractive candidates for growth modulation techniques with the potential advantage of preserving spinal motion segments and avoiding fusion while avoiding the potential adverse psychosocial effects of bracing.

37.3.1 Growth Modulation

Growth modulation techniques rely on the Hueter-Volkmann principle, which states that skeletal growth is inhibited by increased mechanical compression and accelerated by reduced loading when compared to normal values [36]. This principle has been well accepted and popular for the treatment of lower limb angular deformity since Blount and Clarke [37] were the first to report lower extremity angular correction with hemiepiphyseal stapling. When applied to spinal deformity, the goal of treatment is curve control by inhibiting growth on the convex side of a curve while letting the uninstrumented concave side grow unimpeded to allow for gradual curve correction. Animal studies using a rat tail model confirm the ability to modulate vertebral growth plates with skeletal fixation devices [38, 39].

The two primary strategies for growth modulation in the developing spine are vertebral body stapling (VBS) and vertebral body tethering (VBT). Both of these procedures involve MIS instrumentation with tension applied across the convexity of the deformity to facilitate gradual curve correction. Implantation in the thoracic spine is usually thoracoscopically assisted; in the lumbar spine, it is through a direct or extreme lateral retroperitoneal approach.

37.3.2 Vertebral Body Stapling

There are several animal studies supporting the use of stapling for scoliosis correction while preserving motion [40–42]. Although this kind of unilateral epiphysiodesis was initially described as early as the 1950s [40, 43], the technique fell out of favor due to a significant complication rate, including implant dislodgement. Newer metallurgy and a renewed interest in growth modulation has led to a revival of this technique.

Modern staples made of nitinol were recently cleared by the US Food and Drug Administration for orthopedic implantation in the hand, foot, long bones, and spine (on a single vertebra not spanning the disc space). Nitinol is a biocompatible shape memory alloy of approximately 50% nickel and 50% titanium. Nitinol staples have two or four prongs that are straight when cooled and crimp down when warmed to body temperature after implantation (Fig. 37.5a). The shape transformation induces compression between the tines and significantly increases the pullout force necessary to move the staple. Injury to surrounding tissues during transformation has not been reported in animal [44] or human experience with cervical spine fusions [45–47].

As this is a growth-modulating procedure, VBS is only indicated for skeletally immature patients with significant growth remaining as assessed by Risser [48] staging of the iliac apophysis (Risser 0–3) or Sanders' hand X-ray grading (0–3) [49]. Moderate curves (thoracic <35°, lumbar <45°) should be considered for the procedure [50]. We also recommend that the curve must be flexible, bending to less than 20°, to consider VBS. The skeletal maturity and spinal deformity magnitude of patients best indicated for this procedure resemble those of patients for whom brace treatment is also a viable option.

37.3.2.1 Surgical Technique

General anesthesia is utilized and a double lumen endotracheal tube is used to collapse the convex lung. Patients are positioned on a non-flexed table in the lateral decubitus position with the convex side of the scoliosis in the upright position. Proper patient positioning and portal placement are confirmed with fluoroscopic imaging. All vertebrae in the Cobb angle are stapled. For thoracic curves, a thoracoscopic-assisted approach is preferred. The first portal is made in the fifth to seventh intercostal interspaces along the anterolateral chest line. Additional portals are made in the posterior axillary line for insertion of the staples. Fluoroscopic imaging is used to confirm the levels to be stapled. A staple trial is used to determine the correct staple size (4–14 mm) and to create pilot holes (Fig. 37.5b, c). Staples are cooled over a basin of ice, prior to being placed into the pilot holes (Fig. 37.5d). Once inserted and the position confirmed by fluoroscopy, final seating is completed with a tamp. Typically, two single staples or one double staple is placed laterally, spanning each disc space of the measured Cobb angle. In most cases, the parietal pleura does not need to be excised and the segmental vessels can be preserved. On occasion, it is necessary to make a small incision parallel to the segmental vessels to allow movement of the vessel away from the staple prong. If there is significant hypokyphosis (kyphosis < 10°) at the apex of the thoracic curve, the staples are placed more anteriorly on the vertebral body, or a third staple is placed along the anterolateral aspect of the vertebral body. Proper staple positioning is confirmed by fluoroscopic images. If a staple is not in the desired position, it is pulled out with a removal instrument and repositioned. The incisions are closed and a chest tube placed to allow drainage of any effusions and to prevent pneumothorax.

37.3.2.2 Postoperative Protocol

Patients wear a custom, non-correcting thoracolumbosacral orthosis (TLSO) full time for 4 weeks to allow the staples to stabilize. After brace removal, there are no restrictions on physical activity. Patients are seen postoperatively at 1 and 2 months for wound inspection and then at 6-month inter-

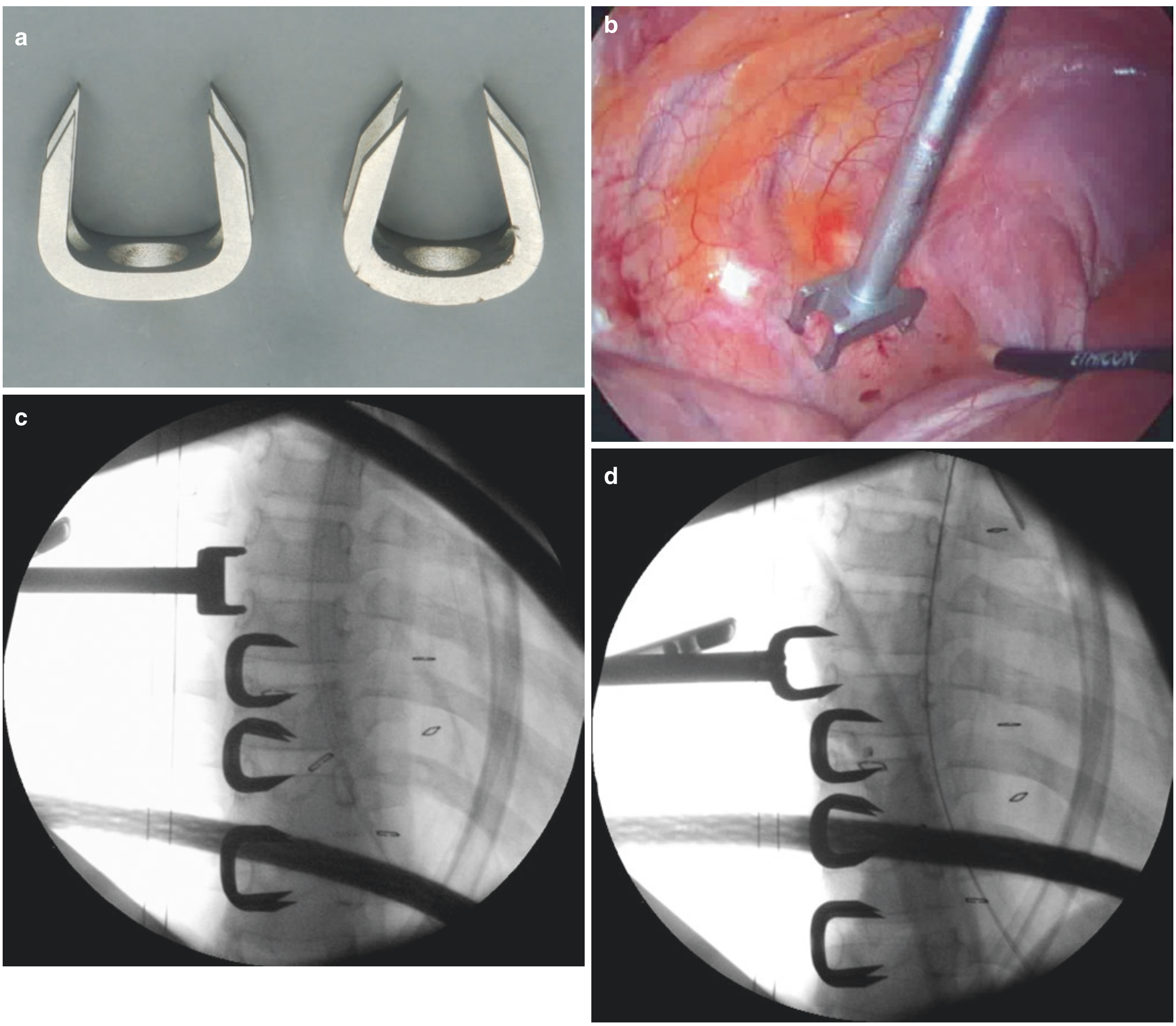

Fig. 37.5 (**a**) A four-prong nitinol staple in the undeployed position near 0 °C and in the deployed position at room temperature; a four-pronged trial positioned against the lateral spine as seen via (**b**) thoracoscopy and (**c**) PA fluoroscopy (**d**). A fluoroscopic image of the staple being inserted in the starting holes created by the trial (**e**). Standing preoperative PA and (**f**) 2-year postoperative standing PA of a skeletally immature male who underwent vertebral body stapling for moderate idiopathic scoliosis

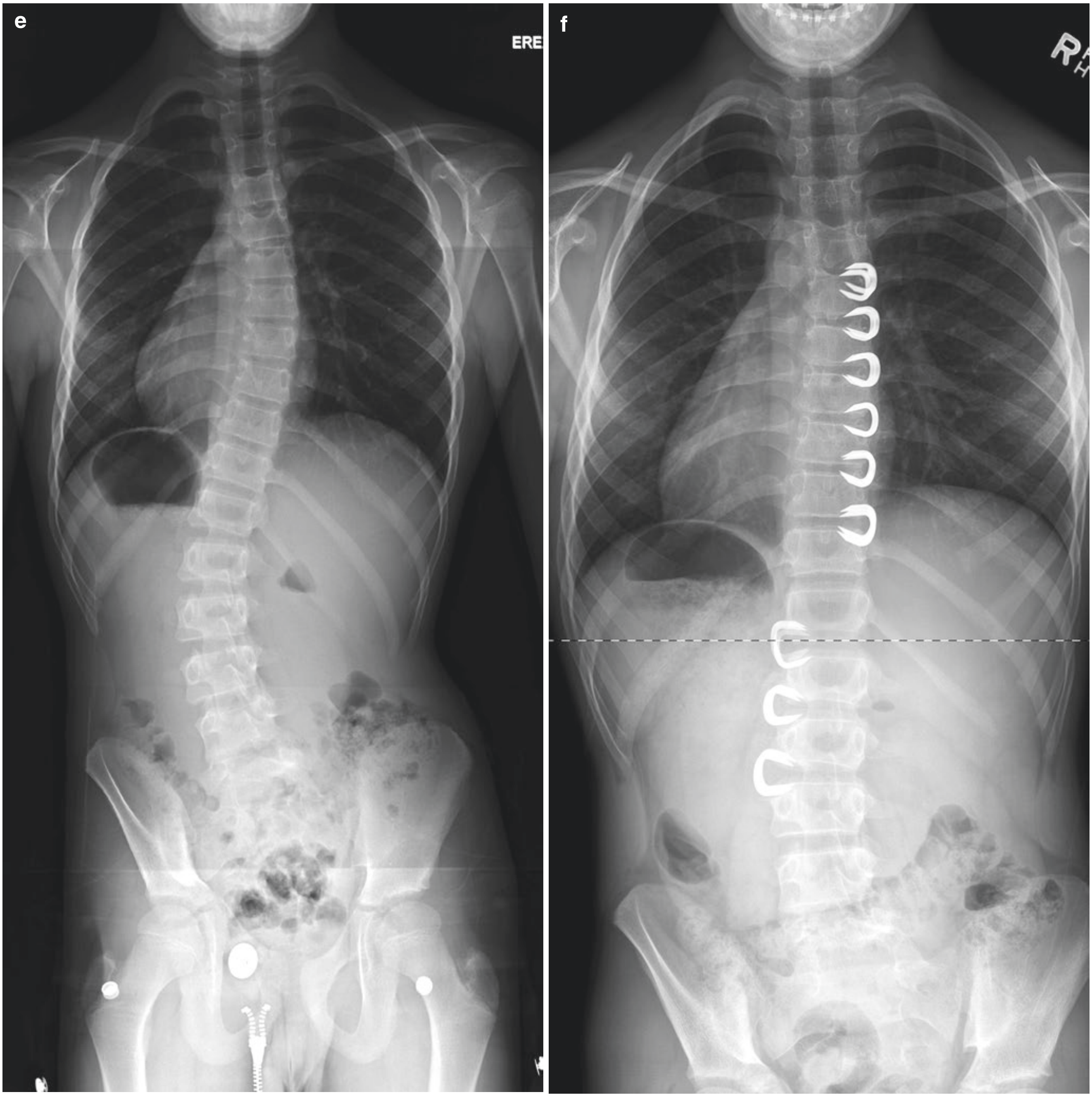

Fig. 37.5 (continued)

vals. Standing posteroanterior and lateral radiographs from the cervicothoracic junction to the sacrum are obtained at each 6-month visit.

37.3.2.3 Results

A series presented by Betz et al. [51] included 26 thoracic and 15 lumbar curves in 28 patients with an average follow-up of 3.2 years. Thoracic curves <35° preoperatively had a success rate of 77.7% and lumbar curves demonstrated a success rate of 86.7%. Of the 8 thoracic curves measuring >35° preoperatively, VBS was successful in halting progression only 25% of the time. One patient in the series developed overcorrection of deformity.

Theologis et al. [52] reported outcomes of 13 curves of 30° to 39° in patients younger than 10 years with idiopathic scoliosis treated with VBS. All 13 curves (thoracic, $n = 9$; lumbar, $n = 4$) were treated successfully at average follow-up of 3.4 years with no significant change in curve magnitudes during the postoperative period.

Bumpass et al. [53] reported on outcomes of 35 patients with a mean age of 10.5 years (range 7.0–14.6 years) treated with VBS. Of the 33 stapled curves available at follow-up, 61% were controlled to less than 10° of progression. Eleven patients (31%) progressed and required subsequent spinal fusions and two curves (6%) over-corrected. Thoracic curves magnitude >35° at time of surgery was a significant risk factor treatment failure, as 83% of these cases progressed beyond 50° despite stapling. Preoperative supine flexibility >30% was predictive of successful curve control with VBS.

O'Leary et al. [54] examined open VBS in a heterogeneous group of 11 patients with syndromic scoliosis, neuromuscular scoliosis, and idiopathic scoliosis. Average preoperative coronal deformity was 68°. At an average of 2-year follow-up, 5 of the 11 patients had already undergone secondary surgical procedures for progression of scoliosis and 3 of the remaining 6 patients were scheduled for secondary surgery. This series highlights the limitations of VBS in severe, non-idiopathic deformities.

Laituri [55] reported outcomes on 7 patients who underwent thoracoscopic VBS for JIS with a mean preoperative coronal deformity of 34°. At a minimum of 2-year follow-up, mean Cobb angle was 24.7°, and no patients had progressed to require spinal fusion.

Cahill et al. [56] recently published the largest series on VBS for idiopathic scoliosis. The series included 63 patients with a minimum of 2-year follow-up (mean of 3.62 years). All patients were Risser sign 0 or 1 with a preoperative coronal curve magnitude of 20–35° for thoracic curves or 20–45° for lumbar curves. The mean pre-op Cobb angle for stapled thoracic curves was 29.5° which improved to 21.8° at most recent follow-up. The mean pre-op Cobb angle for stapled thoracic curves was 31.1° which improved to 21.6° at most recent follow-up. Seventy-four percent of the patients in the thoracic group and 82% of patients in the lumbar group had successfully avoided progression and/or fusion at most recent follow-up. Complications included staple movement or loosening (8% of patients), unilateral localized sympathetic dysfunction in a foot following surgery (3% of patients), atelectasis requiring intervention (3% of patients), and superior mesenteric artery (SMA) syndrome (3% of patients). Four patients demonstrated overcorrection of a stapled curve by most recent follow-up, and three of these patients had undergone staple removal with associated curve stabilization.

Cuddihy et al. [57] performed a matched comparison study between bracing (TLSO) and VBS in skeletally immature patients (Risser sign of 0 or 1) with curves measuring 25–44° at first visit. All patients were 8 years or older. For patients with initial thoracic curves 25–34°, VBS was successful in preventing curve progression of <10° in 81% of cases compared to 61% of cases treated with bracing ($P = 0.16$). In contrast, VBS was successful in preventing curve progression <10° in only 18% of cases with a preoperative thoracic curve of 35–44°, compared to 50% of cases treated with bracing ($P = 0.19$). VBS and bracing were equally successful (~80%) at preventing curve progression in lumbar curves measuring between 25° and 34°.

In conclusion, preliminary results of VBS demonstrate modest ability to prevent deformity progression in high-risk, skeletally immature patients. Significant preoperative deformity (>35°) is a recognized risk factor for failure in thoracic curves. Lumbar curves up to 45° can be reliably treated with VBS. The procedure is safe and the use of staples does not preclude future surgery should curve progression occur and fusion be deemed necessary. However, more research is needed to further elucidate the role of VBS in pediatric spinal deformity surgery.

37.3.2.4 Case Example

A 12-year-old male presented with moderate idiopathic scoliosis with a 25° right thoracic curve and a 33° left lumbar curve (Fig. 37.5e). He was skeletally immature with open triradiate cartilages. According to recent work by Dimeglio et al. [27], he has a 100% risk of progression to a magnitude requiring fusion (50°). He underwent right thoracoscopically assisted VBS and left mini-open retroperitoneal VBS. His curves measured 10° thoracic and 5° lumbar on his first erect radiograph after surgery. At 2 years after surgery, his thoracic curve remains 11° and his lumbar curve at 10° (Fig. 37.5f). His triradiate cartilages are now closed and he is Risser 2. An untreated male with similar maturity and curve magnitude has a 0% chance of progression to fusion according to the data from Dimeglio et al. [27]. VBS prevented this young patient from requiring a spinal fusion.

37.3.3 Vertebral Body Tethering

Due to the poor outcomes of vertebral stapling for thoracic curves larger than 35°, vertebral body tethering has emerged as a new preferred technique for instrumented spinal growth modulation. First described by Crawford and Lenke [58], tethering involves placement of anterior vertebral body screws on the convexity of a thoracic or lumbar curve. Instrumentation may be placed through an open or thoracoscopic technique. Following screw placement, a flexible tether is seated into the screws and sequentially tensioned to achieve partial curve correction. Similar to the design of staples, the tether construct acts as an impediment to convex spine growth while allowing for continued growth on the concavity of the curve.

VBT achieves a more powerful corrective force compared to stapling, but with a higher potential for overcorrection. As such, VBT is better utilized for curves of larger magnitude. Current indications for VBT include skeletal immature patients (Risser 0–3) with idiopathic thoracic major scoliosis of 45–65° without structural compensatory curves.

37.3.3.1 Technique

After single lung ventilation is achieved by the anesthesia team, the patient is positioned in the lateral decubitus position and the flank is widely prepped and draped in the event emergent access to the chest is needed. Fluoroscopy is utilized to plan levels of instrumentation and portal placement (Fig. 37.6).

Thoracoscopic access to the chest is then obtained by making two portals in the anterior axillary line to accommodate 5 mm cannulas. We prefer to perform the access in collaboration with a pediatric thoracic or general surgeon. A 30-degree thoracoscope is then brought through the inferior of the two portals, and carbon dioxide insufflation is used to assist in deflating the lung completely to allow for visualization of the spine. A pleurectomy followed by sequential ligation of the segmental vessels on the convexity of the spine is performed across the intended levels of instrumentation. Communication with the neuromonitoring team is critical should ischemia to the spinal cord occur due to segmental vessel ligation. Next, lidocaine is used to localize and identify the trajectory for instrumentation from directly lateral. In general, two lateral portals are made to accommodate 15 mm portals at the cranial and caudal thirds of the convexity.

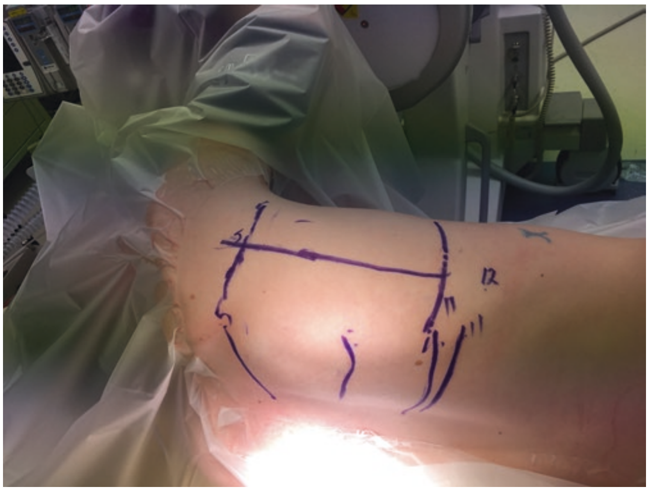

Fig. 37.6 Patient is positioned in the left lateral decubitus position. Prior to prep and drape, a fluoroscopy is used to identify landmarks and plan levels for thoracoscopy

Instrumentation is then placed, beginning with a centering staple placed directly over the lateral aspect of the vertebrae with both direct visualization and AP and lateral fluoroscopic confirmatory imaging (Fig. 37.7a). A tap is passed across the vertebrae while confirming appropriate trajectory on fluoroscopy (Fig. 37.7b), followed by a hydroxyapatite-coated monoaxial screw (Fig. 37.7c). Screws are typically placed from caudal to cranial, utilizing various intercostal windows through each lateral portal.

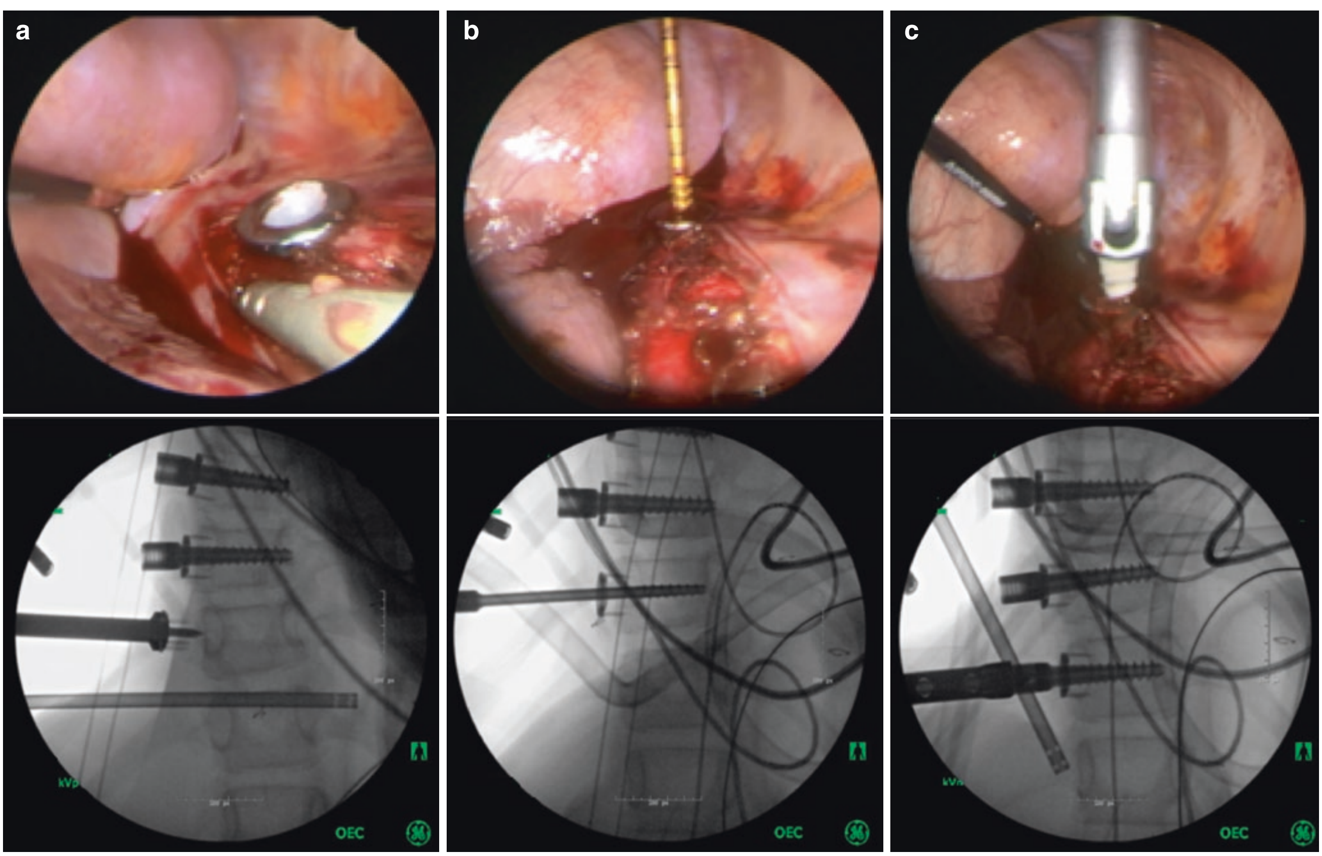

Fig. 37.7 Thoracoscopic and fluoroscopic imaging demonstrate (**a**) a centering staple positioned on the vertebral body, (**b**) tapping the screw trajectory, and (**c**) monoaxial screw insertion

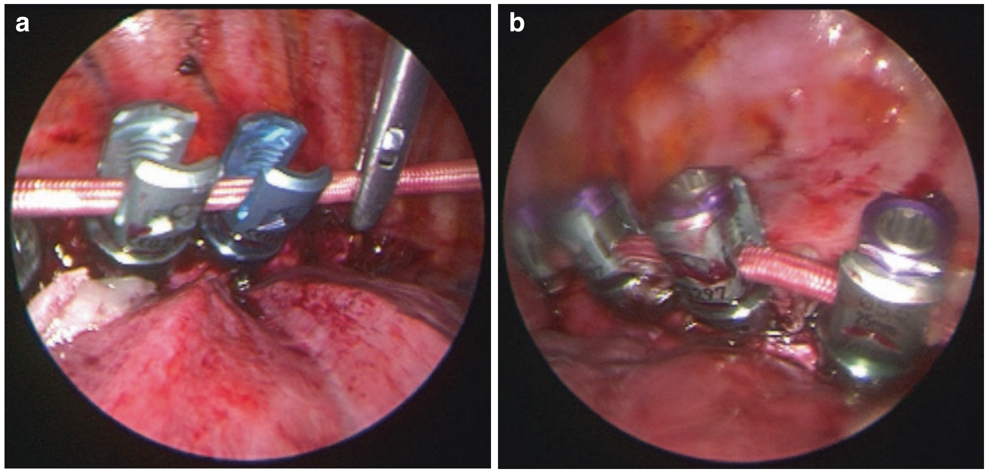

Fig. 37.8 (**a**) After placement of screws, a polyethylene terephthalate cord is introduced to function as a tether. (**b**) The cord is tensioned sequentially at each level until the end plates are parallel, and set screws are employed to lock the tether in place

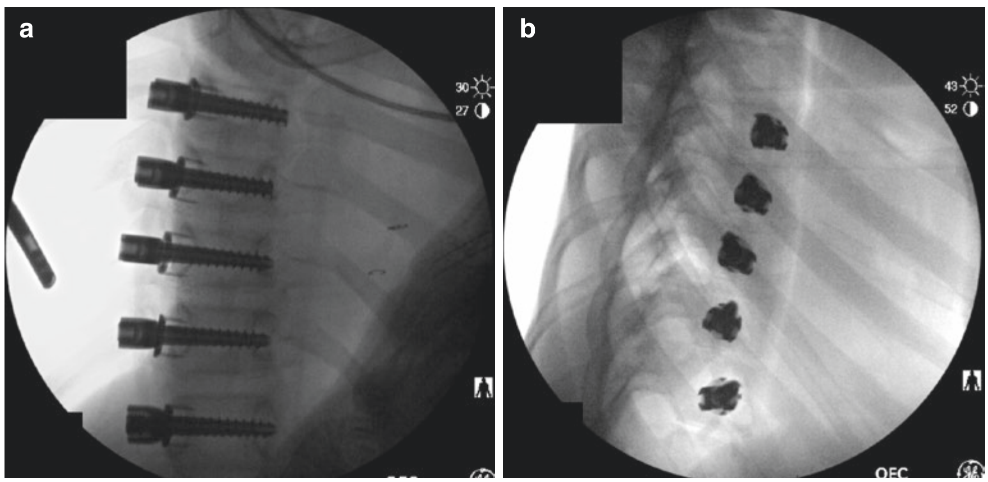

Fig. 37.9 (**a**) AP and (**b**) lateral fluoroscopic images after the tether has been adequately tensioned, demonstrating leveling of the endplates in the coronal plane

After instrumentation has been placed and verified with imaging, a polyethylene terephthalate cord is introduced and captured proximally with a set screw (Fig. 37.8a, b). A tensioning device is then introduced and the synthetic cord is tensioned and locked with a set screw once the endplates have been brought parallel, as confirmed under fluoroscopic imaging (Fig. 37.9a, b). This is performed sequentially for each level. If additional correction is needed for the most cranial level, the tether can be grasped proximal to the most cranial screw and, after the set screw is loosened, tensioned around a thoracoscopic grasper to impart further tension.

37.3.3.2 Postoperative Protocol

At the conclusion of the case, intercostal blocks are performed under direct thoracoscopic visualization to aid in pain control. A chest tube is placed to suction to assist in reinflation of the collapsed lung and can typically be removed when output is less than 200 mL/24 h. A confirmatory chest radiograph is taken a few hours following removal to confirm appropriate aeration of the lung and no sign of re-collapse. Aggressive pulmonary toilet and incentive spirometry, coupled with early ambulation, are paramount to the postoperative recovery after the procedure. Patients are permitted to return to activities of daily living as soon as they are comfortable. At 6 weeks postoperatively, most patients are permitted to return to all activities without restrictions.

37.3.3.3 Results

Samdani [59] reported outcomes on 32 skeletally immature patients (mean Risser score 0.42, mean Sanders score 3.2) with thoracic idiopathic scoliosis with a minimum of 1 year following thoracoscopic tethering. Thoracic curve magnitude improved from 42.8° preoperatively to 21.0° at first erect films and 17.9° at most recent follow-up. The lumbar curve improved significantly as well from 25.2° preoperatively to 9.4° at most recent follow-up. Thoracic rotation, as measured by scoliometer, improved significantly as well from 13.4° preoperatively to 7.4° at recent follow-up. One patient experienced prolonged postoperative atelectasis, and three patients developed overcorrection.

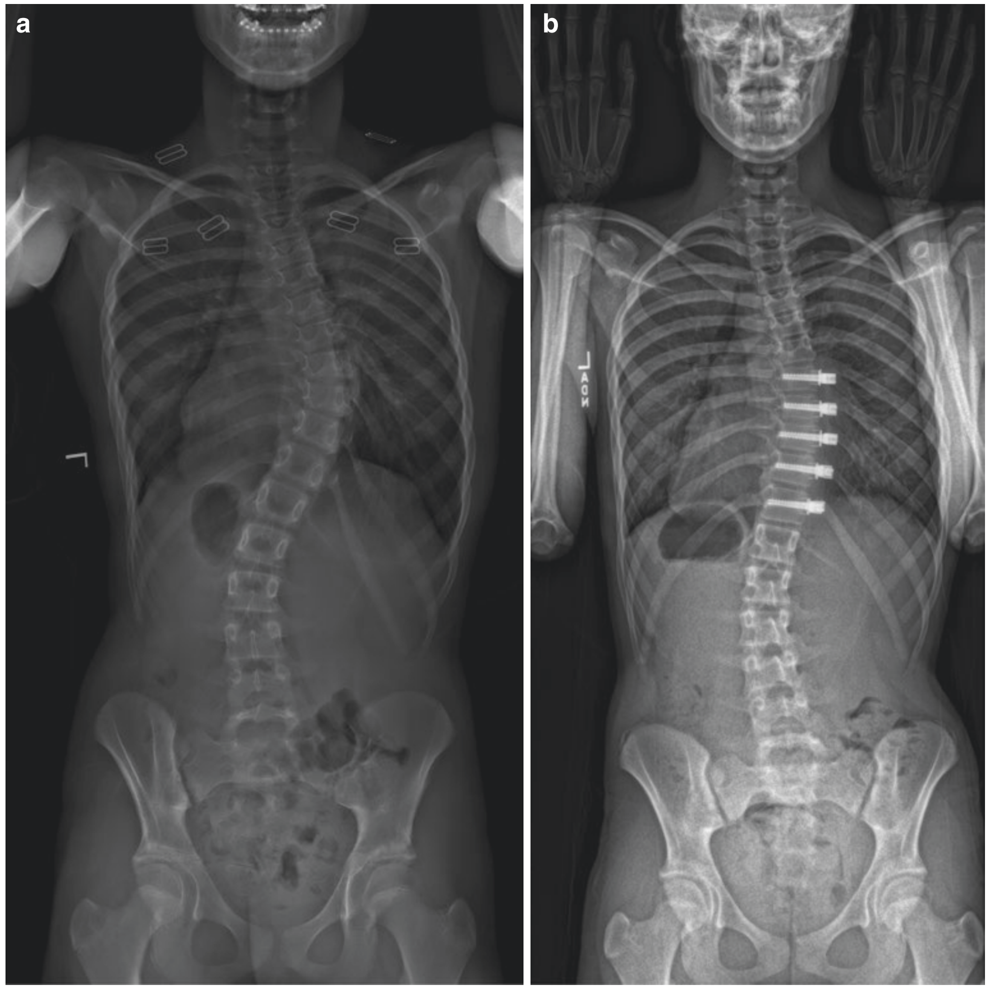

Fig. 37.10 PA radiograph (**a**) preoperatively and (**b**) 1 year postoperatively following anterior thoracoscopic vertebral body tethering

Samdani [60] also presented outcomes of a subset of 11 patients with idiopathic scoliosis who had reached the 2-year follow-up after tethering of an average of 7.8 vertebral levels. Thoracic curve magnitude improved from 44.2° preoperatively to 20.3° at first erect films and 13.5° at 2-year follow-up. Two patients required reoperation to loosen the tethering for concerns of overcorrection. Both curves stabilized following reoperation.

Newton et al. [61] recently presented outcomes from their institution following 17 cases of VBT for idiopathic, cardiac, and syndromic scoliosis. All patients had thoracic curves (40–67°, mean 52°) and the mean number of instrumented vertebrae was 6.8. 59% of patients (10/17) were considered a clinical success, defined as a curve <35° at most recent follow-up of 2–4 years. Curve correction due to growth modulation averaged 8° + 17° but with a wide range across patients (36 to −26°). Ten additional surgeries in eight patients were either performed or planned including four tether removals due to overcorrection, one replacement of a broken tether, and addition of a tethering construct to a contralateral lumbar curve. One patient had been converted to a PSIF and three more were planned for PSIF secondary to curve progression despite tethering.

In conclusion, tethering appears to be a powerful technique for growth modulation in the skeletally immature patient with spinal deformity. However, there is a significant complication rate including hardware issues and overcorrection. Although the material the tether is made of (polyethylene terephthalate) is approved for use in humans, the long-term biocompatibility of this material in this application is unknown. While instances of macroscopic failure (e.g., breakage) of the tether have been described [61], microscopic failure (e.g., wear debris) has not been reported at midterm follow-up. The indications for vertebral tethering have not been clearly established, and various opinions exist regarding which patients should be considered for this relatively new approach to treating scoliosis. Further high-level research, including observational studies and randomized trials, will be critical to clarifying the indications and outcomes of VBT in pediatric spinal deformity.

37.3.3.4 Case Example

A 12-year-old pre-menarchal female had moderate idiopathic scoliosis with a 50° right thoracic curve and a 31° compensatory left lumbar curve (Fig. 37.10a). She was skeletally immature (Risser stage 0 and Sanders stage 3) indicating a high likelihood of curve progression, and already in the surgical range for adolescent idiopathic scoliosis. After discussing various treatment strategies, the patient and family elected to undergo an anterior thoracoscopic vertebral body tethering from T7 to T11. Her curves measured 31° thoracic and 25° lumbar on upright radiographs after surgery. At 1 year after surgery, her thoracic curve is 24° and her lumbar curve at 19° (Fig. 37.10b). She is now post-Menarchal, Risser stage 2, and Sanders 5.

> Spinal growth modulation techniques may allow for fusion-less treatment of pediatric spinal deformity, but further research is needed regarding long-term outcome.

37.4 Chapter Summary

Although the adoption of MIS techniques for the treatment of spinal deformity is in its infancy, pioneering advances in the field are emerging. Surgeons are applying principles of minimizing soft tissue disruption to existing procedures such as posterior spinal fusions with promising results. Several surgeons are also adapting the principles of preservation of structural anatomy and motion in innovative ways as evidenced by emerging interest in thoracoscopic vertebral body stapling and vertebral body tethering.

Summary

1. MIS and LIS techniques and principles are being applied to pediatric spinal deformity
2. Less invasive posterior spinal fusion for adolescent scoliosis is possible through transmuscular instrumentation with preservation of the midline attachments of the paraspinal muscles
3. Thoracoscopy allows for minimally invasive anterior release and/or instrumentation and fusion
4. Spinal growth modulation techniques, such as vertebral body stapling and vertebral body tethering, may allow for fusion-less treatment of pediatric spinal deformity, but further research is needed regarding long-term outcome

Quiz Questions

1. A 14-year-old female with AIS presents with a flexible right thoracic curve that has progressed to 50°. She is Risser 0, Sanders 3, and pre-menarchal. The family wishes to discuss all surgical options. The options you may discuss for this patient include:
   (a) Posterior instrumented spinal fusion
   (b) Vertebral body stapling
   (c) Vertebral body tethering
   (d) (b) and (c)
   (e) (a) and (c)
2. There are several potential advantages to MIS posterior spinal fusion. What is a potential disadvantage of this technique compared to the traditional open exposure?
   (a) Decreased screw placement accuracy
   (b) Decreased curve correction
   (c) Increased use of fluoroscopy
   (d) Increased infection rate
   (e) Increased length of hospital stay
3. Anterior access to the spine can be gained through a thoracoscopic approach. The patient may be placed in lateral decubitus or prone. Advantages of the prone position include:
   (a) Increased efficiency when also performing PSF
   (b) Single lung ventilation is required
   (c) No risk of lung injury
   (d) Ease of portal placement
   (e) All of the above

Answers

1. (e) This skeletally immature female still has significant growth remaining. This curve falls into the range where traditional posterior spinal fusion or growth modulation with VBT may be considered. VBS has been less reliable in thoracic curves larger than 35°.
2. (c) Long-term follow-up is needed to confirm short-term results of MIS techniques for PSF in AIS including decreased average blood loss. Equivalent screw placement accuracy and curve correction are reported with no increased length of hospital stay. Image guidance is paramount to accurate placement in MIS techniques, with potential for increased radiation exposure through increased fluoroscopy time
3. (a) Prone position for the thoracoscopic approach allows increased efficiency when also performing PSF as it avoids the need to reposition the patient. The lung may stay inflated as gravity pulls it forward and single lung ventilation is not required, as it is for lateral decubitus position when the ipsilateral lung is deflated. Careful

wide prep and draping must be used in order to facilitate portal placement. In any thoracoscopic approach, risk of injury to the lung exists and care must be taken to ensure the lung is out of the way of the thoracoscopic instruments either through positioning or lung deflation

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