Original Article

Hardware failure following multilevel posterior percutaneous fixation using the minimally invasive antepsoas (MIS-ATP) approach in adult spine deformity

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Background: Adult spinal deformities (ASDs) requiring long fusions to the lumbosacral junction are notorious for L5–S1 pseudarthrosis and hardware-related complications. The minimally invasive surgery antepsoas (MIS-ATP) technique allows for substantial anterior column reconstruction thereby reducing the risk of posterior hardware-related complications. This study investigates the incidence of posterior hardware-related complications following long-segment fusion (seven or more vertebrae) using MIS-ATP and posterior percutaneous fixation (PPF).

Methods: This is a retrospective review of patients who underwent long spinal fusion (MIS-ATP + PPF) to the sacrum and pelvis for the management of ASD between 2008 and 2019. Postoperative clinical complications and radiographic parameters were collected and analyzed. The following postoperative variables were collected: surgical site infections, neuro-vascular injuries, implant fracture, implant displacement, hardware prominence and related pain, pseudarthrosis, junctional disease (proximal and distal), and need for surgical revision.

Results: A total of 143 patients were included in this study. The most common indications for fusion included: degenerative scoliosis (76.9%) and degenerative spondylolisthesis (17.5%). The average number of fused vertebrae per individual was 8.7. The most common levels fused were: T12–S1 anterior/T10–S1 posterior (53.1%). Forty-four patients (30.8%) experienced a total of 48 complications: pseudarthrosis (2.1%), deep infections (4.2%), painful iliac hardware (5.6%), pedicle screw complications (6.3%), and proximal junctional disease (PJD) (9.8%). Of these, 30 patients (21%) required revision surgery, mostly due to PJD (8 patients; 5.6%).

Conclusions: Long spinal fusions to the sacrum and pelvis are technically challenging and notorious for hardware failure (HF) and revision surgeries. The use of MIS-ATP fusion coupled with PPF could provide a safe and effective strategy against posterior HF. Furthermore, additional benefits of the MIS-ATP technique are inherent to its relatively safe approach-related profile.

Keywords: Antepsoas (ATP); hardware failure (HF); posterior percutaneous fixation (PPF); minimally invasive surgery ATP (MIS-ATP); thoracolumbar fusion

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Introduction

Adult spinal deformities (ASDs) requiring long spinal fusions (seven or more vertebrae), spanning the thoracolumbar and the lumbosacral junctions, are notorious for pseudarthrosis, hardware-related complications, and proximal/distal junctional diseases. Distal hardware failure (HF) can develop secondary to substantial flexion moments, posterior cantilever forces, and poor bone quality at L5 and S1 (1-5). To avoid these challenges, several solutions for lumbosacral fixation have been described (1,2,4,6-8). Despite the common use of iliac and sacroiliac fixations, the occurrences of lumbosacral junctional pseudarthrosis, loss of posterior fixation, and/or painful hardware requiring revision remain high (3,5,9,10). On the other hand, relying on the addition of anterior structural column support instead of posterior fusion has been advocated by many to increase stability and avoid posterior HFs (2,11-13). The minimally invasive surgery antepsoas (MIS-ATP) approach offers an alternative method to the direct anterior and transpsoas techniques for lumbar interbody fusion utilizing the expandable natural psoas-vascular corridor to reduce the risks of vascular, visceral, and neural injuries. The minimally invasive MIS-ATP technique avoids open posterior fusion by allowing an oblique retroperitoneal prepsoas access and substantial anterior column support between T12–S1 for anterior fusion and leaving the posterior for percutaneous fixation (14,15). Using this approach, several complications associated with open instrumentation can be mitigated. While supportive evidence exists for deformity correction using other minimally invasive techniques with posterior percutaneous fixation (PPF), the rate of HF is not well-defined for patients undergoing MIS-ATP and PPF for ASD (16-21). This study aims to determine the rate of postoperative complications and posterior hardware-related failures in patients treated with long-construct anterior-posterior fusion using the MIS-ATP approach coupled with PPF. We present this article in accordance with the STROBE reporting checklist (available at https://jss.amegroups.com/article/view/10.21037/jss-23-127/rc).

Highlight box

Key findings

- The minimally invasive surgery antepsoas (MIS-ATP) approach coupled with posterior percutaneous fixation (PPF) is a viable treatment option for adult spinal deformity (ASD) correction in terms of posterior hardware failure (HF).

What is known and what is new?

- ASD requiring long spinal fusion to the sacrum are known for their high rate of HF especially with open instrumentation. Emerging studies focusing on minimally invasive procedures with or without PPF looked at rates of HF.
- The MIS-ATP technique avoids open posterior fusion by allowing an oblique retroperitoneal prepsoas access and substantial anterior column support for anterior fusion and leaving the posterior for percutaneous fixation. Using this approach, several complications associated with open instrumentation can be mitigated.

What is the implication, and what should change now?

- The use of MIS-ATP fusion coupled with PPF could provide a safe and effective strategy to mitigate posterior HF.
- MIS-ATP should be considered in patients requiring long fusion for ASD correction.

Methods

This is a retrospective review of 143 patients who underwent long spinal fusion of seven segments or more (MIS-ATP + PPF) to the sacrum with (n=127) and without (n=16) iliac fixation for the management of ASDs between 2008 and 2019 at Boston University Medical Center (*Figures 1,2*). Surgery was performed based on the preference of two minimally invasive spine-trained surgeons. ASD was defined as the presence of one or the combination of any of the following: spondylolisthesis, lateral or rotatory subluxation, segmental instability, sagittal imbalance, coronal imbalance, or scoliosis. All patients had titanium rods of 5.5 mm in diameter and cages were typically packed with corticocancellous bone allograft mixed with autologous non-concentrated vertebral bone marrow aspirate. No additional biologics or bone graft substitutes were used. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the institutional review board of Boston University (No. H-36834) and individual consent for this study was waived due to its retrospective nature.

The collected demographic, clinical, and surgical information included: age, gender, smoking status, follow-up duration (months), the primary diagnosis, primary or revision surgery, and the number of levels fused. Lumbar lordosis (LL: T12–S1), pelvic incidence (PI), pelvic tilt (PT), and coronal Cobb angle were measured at three checkpoints: preoperative, immediately post-operative, and last follow-up (at least 6 months postoperative). A total of 136 patients were included for radiographic measurements as patients with prior fusion surgery were deemed ineligible (n=7). Patients were excluded if they did not receive a

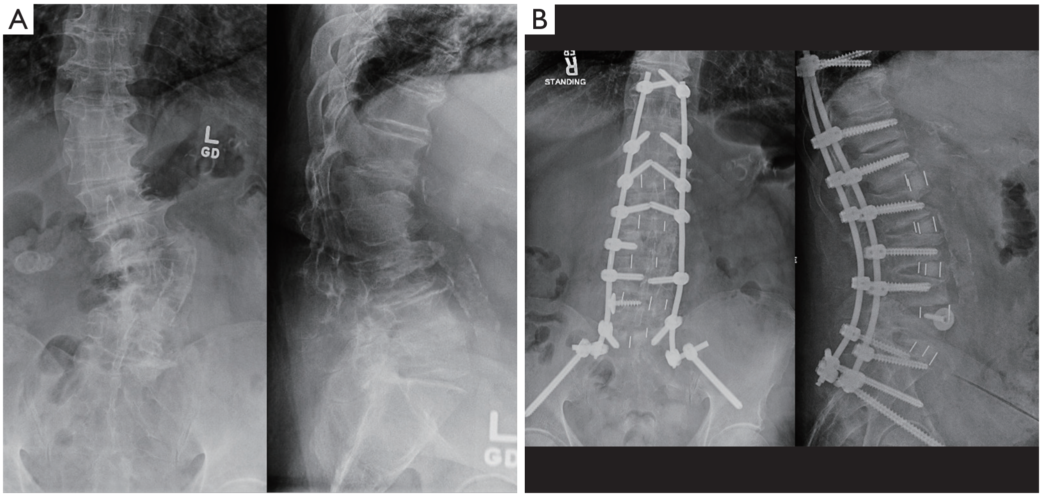

Figure 1 Patient case undergoing MIS-ATP + PPF long fusion. (A) Preoperative anteroposterior and lateral view X-rays demonstrating adult degenerative scoliosis. (B) Anteroposterior and lateral view X-rays of a MIS-ATP long spinal fusion with pelvic fixation. Permission use request was granted by Wolters Kluwer Health, Inc. (license: 5726840365092). MIS-ATP, minimally invasive surgery antepsoas; PPF, posterior percutaneous fixation.

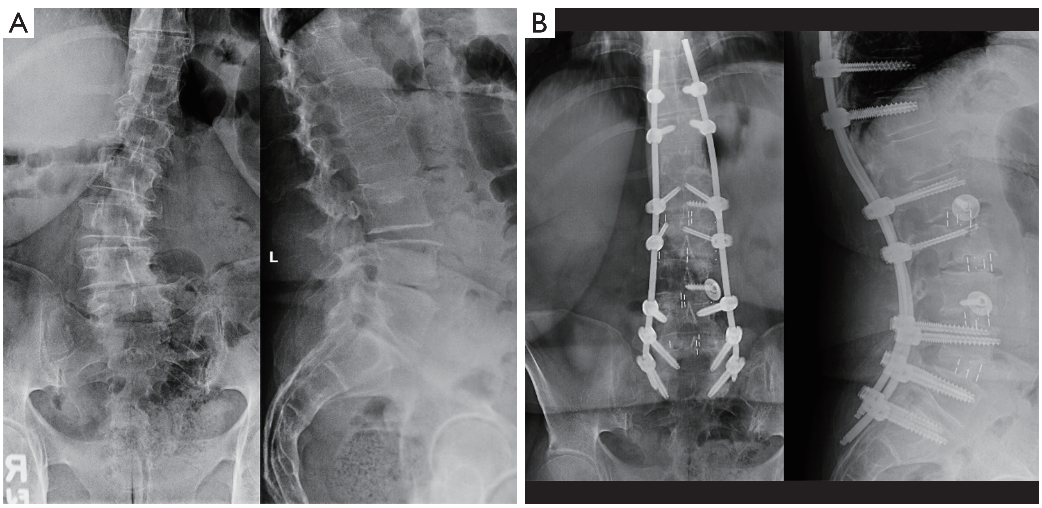

Figure 2 Patient case undergoing MIS-ATP + PPF long fusion with sacropelvic fixation. (A) Preoperative anteroposterior and lateral view X-rays demonstrating adult degenerative scoliosis. (B) Anteroposterior and lateral view X-rays of a MIS-ATP long spinal fusion without pelvic fixation. MIS-ATP, minimally invasive surgery antepsoas; PPF, posterior percutaneous fixation.

combined anterior/posterior fusion through the ATP approach and if they were primarily treated for deep spinal infections or oncologic disorders. In all patients, and prior to surgery, spine radiographs and advanced imaging were examined for any advanced degenerative changes. All levels with moderate or severe degenerative disease were included in the fusion constructs, while normal discs and ones with mild degenerative changes of no clinical significance were spared. All patients' radiographs and medical charts were evaluated to determine the occurrence of operative/postoperative clinical and radiographic complications. These included surgical site infections, transient anterior thigh pain, new neurologic deficits, vascular/visceral injuries, hardware fracture, HF, junctional (proximal and distal) diseases, pseudarthrosis, and need for revision surgeries. While rod breakage and pedicle screw-related complications

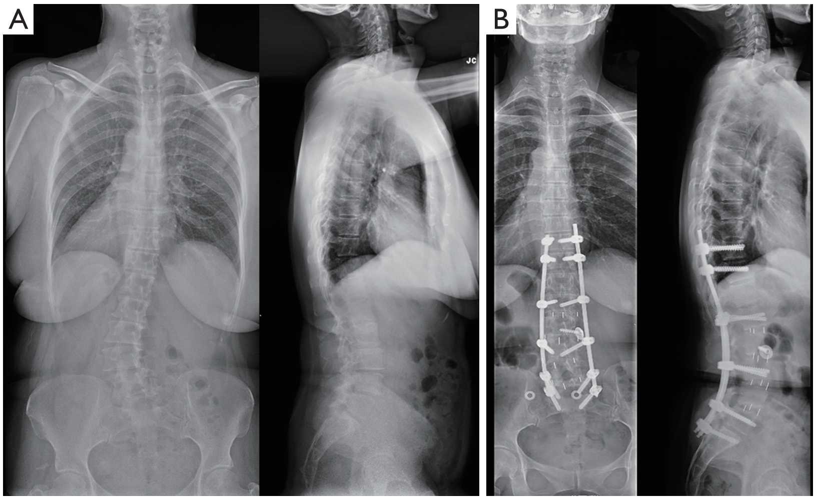

Figure 3 Patient case with transitional anatomy undergoing MIS-ATP + PPF. (A) Preoperative anteroposterior view (left) and lateral view (right) X-rays demonstrating lumbarized S1 transitional anatomy. (B) Postoperative anteroposterior view (left) and lateral view (right) X-rays demonstrating long spinal fusion with four points of sacral fixation. MIS-ATP, minimally invasive surgery antepsoas; PPF, posterior percutaneous fixation.

can pertain to pseudarthrosis, these findings occurred despite adequate union [using a computed tomography (CT) scan] and thus were classified as an independent category. Pseudarthrosis, although associated with implant failures, is utilized to describe the lack of intervertebral bony fusion irrespective of posterior screws-rods stability.

Statistical analysis

Data analysis was conducted using R and RStudio statistical computing environment version 3.3.2 (Rstudio, Inc., Boston, MA, USA). Repeat measures analysis of variance (ANOVA) was used to compare preoperative, postoperative, and final follow-up groups, with subsequent paired *t*-tests used to evaluate differences between groups. Statistical significance was defined as P<0.05.

Results

All patients (n=143, 72.7% females, average age 65.8 years) underwent a combined anterior-posterior thoracolumbar spinal fusion using the MIS-ATP approach. The average follow-up time is (2.5±0.6 years). None of the patients received open posterior release, osteotomy, or instrumentation. Sixteen patients did not receive a pelvic fixation: patients with stiffer lumbosacral junction allowing four or more points of fixation in the sacrum, often have a transitional lumbosacral junction with a non-mobile disc (lumbarized sacral level, or sacralized lumbar level). Under this category, we included patients with lumbarized S1 (received distal bilateral S1–S2 pedicle screws), and patients with sacralized L5 (received distal bilateral L5–S1 pedicle screws) (*Figure 3*). None of these patients, with transitional lumbosacral anatomy (n=16), received additional iliac fixation and none experienced distal junctional failure or lumbosacral pseudarthrosis. The two most common indications for fusion included: degenerative scoliosis (76.9%) and degenerative spondylolisthesis (17.5%). Besides degenerative scoliosis, patients with multilevel stepladder spondylolisthesis resulting in loss of sagittal alignment were included. In terms of tobacco exposure: 62 patients (43.4%) never smoked, 49 (34.3%) were former smokers, and 32 (22.3%) were active smokers. *Table 1* outlines further details regarding demographics and preoperative diagnoses.

The average number of fused vertebrae was 8.7 per subject. Of the 143 patients studied, 136 patients had primary surgeries and 7 had revision procedures for previous spinal fusions (non-MIS-ATP). These patients had prior surgery involving four fused segments on average and received additional extension of fusion of 4.7 segments on average. Revision surgeries, in the latter group, were performed for: adjacent segment disease (n=5, 3.5%) and pseudarthrosis (n=2, 1.4%). The most common levels fused were: T12–S1 anterior/T10–S1 posterior (53.1%). *Table 2*

Table 1 Summary of patient information

Demographics	Value (n=143)
Age (years), average	65.8
Sex, n (%)	
Female	104 (72.7)
Male	39 (27.3)
Smoking, n (%)	
Never	62 (43.4)
Former	49 (34.3)
Active	32 (22.3)
Preoperative diagnosis, n (%)	
Primary surgery	136 (95.1)
Degenerative scoliosis	110 (76.9)
Degenerative spondylolisthesis	25 (17.5)
Degenerative kyphosis	1 (0.7)
Revision surgery	7 (4.9)
Adjacent segment disease	5 (3.5)
Pseudarthrosis	2 (1.4)

Table 2 Distribution of instrumented levels (anterior and posterior)

No.	Location		Frequency	%
	Anterior	Posterior		
1	T12–S1	T10–S1	76	53.1
2	T12–S1	T11–S1	31	21.7
3	T12–L5	T10–S1	7	4.9
4	T12–L5	T11–S1	5	3.5
5	L1–L5	T10–S1	4	2.8
6	L1–S1	T12–S1	3	2.1
7	T12–S1	T12–S1	3	2.1
8	L1–L5	T11–S1	3	2.1
9	T12–S1	T9–S1	2	1.4
10	T12–S1	T7–S1	2	1.4
11	L1–L5	T12–S1	1	0.7
12	L1–L3	T11–S1	1	0.7
13	L2–S1	T12–S1	1	0.7
14	L3–S1	T10–S1	1	0.7
15	T12–L2	T11–S1	1	0.7
16	T12–L4	T10–L5	1	0.7
17	T12–S1	T11–S2	1	0.7

outlines the distribution of levels fused anteriorly and posteriorly.

Forty-four patients (30.8%) experienced a total of 48 complications (*Table 3*). These included deep surgical site infections (n=6, 4.2%), hardware-related complications [iliac screws (ISs) 6.3%, pedicle screws 5.6%, longitudinal rods 2.8%], and proximal junctional disease (PJD) (9.8%). Of these, 30 patients (21%) required a revision surgery, with the most common being due to PJD (8 patients, 5.6%) and painful iliac hardware (7 patients; 4.9%). From the seven patients who had a previous spine surgery, two suffered hardware-related complications with one patient requiring a revision surgery. Out of the 16 patients that did not require sacropelvic fixation, 4 patients (25%) had complications compared to 40 patients (31.5%) out of the 127 patients that had sacropelvic fixation [odds ratio (OR): 1.38; P=0.57]. The complications in the former group were as follows: two rod breakages, one PJD, and one deep infection. No vascular or visceral injuries were observed in the entire series. Eighteen patients (12.6%) suffered from transient anterior thigh pain. The longest period for symptoms resolution took 6 months after surgery.

Hypolordosis was defined as greater than 10° mismatch in PI and LL (PI-LL ≥10°). On average, 7.6° of LL were restored following surgery and 4.3° were maintained at final follow-up in this entire cohort (P<0.05). In total, 56.6% of all patients (n=77) had a PI-LL ≥10° and among patients an average of 12.8° of correction was achieved post-operatively with a correction of 8.1° at final follow-up (P<0.01). Of these hypolordotic patients, 70.1% were corrected to a PI-LL <10° following surgery, with 61.1% of patients maintaining correction at final follow-up (P<0.001). In total, 113 (83%) and 106 (77.9%) patients achieved adequate sagittal alignment following surgery and final follow-up respectively. Twelve patients out of 34 patients with hardware complications had a PI-LL ≥10° while 18 patients out of 102 patients with either no complications or non-hardware complications had a PI-LL ≥10° (OR: 2.54; P=0.03). One hundred and twenty-nine patients (94.9%) achieved a final coronal Cobb angle <10° (P<0.001). Changes in all radiographic parameters are summarized in *Table 4*. The final PI-LL mismatch (P=0.41) and final coronal Cobb angle (P=0.33) between patients with hardware complications (n=34) and patients with no

Table 3 Summary of complications and revision surgeries

Complications	Occurrence	Revision surgery
SSI	9 (6.3)	6 (4.2)
Superficial SSI†	3 (2.1)	0
Deep SSI	6 (4.2)	6 (4.2)
Lumbar, thoracic	3 (2.1)	3 (2.1)
Sacro-pelvic	3 (2.1)	3 (2.1)
Hardware related complications	35 (24.5)	21 (14.7)
PJD	14 (9.8)	8 (5.6)
PJK	10 (7.0)	5 (3.5)
PJF	1 (0.7)	1 (0.7)
ASD	3 (2.1)	2 (1.4)
Pedicle screws related	8 (5.6)	3 (2.1)
Breakage/set screw failure	2 (1.4)	2 (1.4)
Peri-screw lucency	6 (4.2)	1 (0.7)
ISs related	9 (6.3)	8 (5.6)
Acetabulum violation	1 (0.7)	1 (0.7)
Painful/prominent hardware	8 (5.6)	7 (4.9)
Rod breakage/failure	4 (2.8)	2 (1.4)
Pseudarthrosis	3 (2.1)	2 (1.4)
T10–T11	1 (0.7)	1 (0.7)
L3–L4	1 (0.7)	1 (0.7)
L5–S1	1 (0.7)	0
Neurological complications‡		
New leg weakness	1 (0.7)	1 (0.7)
Total	44 (30.8; 48 complications)	30 (21.0)

Data are presented as n (%). †, superficial SSI: outpatient management with local wound care and oral antibiotics; ‡, neurologic complications different from transient anterior thigh pain. SSI, surgical site infection; PJD, proximal junctional disease; PJK, proximal junctional kyphosis; PJF, proximal junctional failure; ASD, adjacent segment disease; IS, iliac screw.

complications or non-hardware complications (n=102) were not significantly different.

Discussion

The MIS-ATP allows for the development of retroperitoneal surgical corridor, anterior to the psoas muscle (*Figure 4*). Using a relatively smaller incision, compared to anterior lumbar interbody fusion (ALIF), this approach grants wide access to the intervertebral disc for adequate discectomy while protecting the prevertebral vessels and reducing the risks of inadvertent vascular complications relative to an ALIF (15). Unlike eXtreme lateral interbody fusion (XLIF), the psoas muscle is preserved during the MIS-ATP approach (13) (*Figure 5*). Despite the evolving instrumentation designs and surgical techniques (4,6,7) with goals to achieve greater deformity correction and provide stability, long fusions to the sacrum in adult patients remain problematic. They can be associated with fixation failure, pseudarthrosis, and postoperative complications (4,6,7,22). The tremendous cantilever forces acting at the lumbosacral junction, combined with the poor bone quality-stock of the lower lumbar and sacral spine, are thought to be implicated (22). Loss of sacral fixation, sacral fractures, loss of LL, wound infection, prominence of instrumentation, and related pain have been well documented (22).

Previously described retroperitoneal thoracolumbar approaches allow for anterior release (i.e., anterior ALL release, osteotomies, vertebrectomies) and fusion using structural autograft and/or allograft (22). On the other hand, posterior corrective procedures rely mainly on bony osteotomies to achieve proper coronal and sagittal balance (22). Additional LL can be gained by positioning the patients prone with free hanging abdomen and hips being supported in full extension (22). The addition of posterior instrumentation is crucial to maintain the surgically corrected lumbar alignment and provide stability for biological fusion. Modern posterior instrumentations include segmental pedicle screw fixation combined with sacral screws, iliac anchorage, and S2-alar-iliac fixation (22).

Hardware complications

Previous literature investigating complications following lumbopelvic fixation reported posterior HF in 8.7–34.3% of treated patients, with 5.3–12% labeled as major failures (8,20). Major failure was defined as revision surgery for rod breakage, failure of pedicle screws (breakage, halo formation, or pullout), or prominent implants requiring removal (8). Using this definition, this series had 21 patients (14.7%) with posterior HF including 13 patients (9.1%) requiring revision surgery for major failures. The authors hypothesize that the MIS-ATP anterolateral fusion, especially at the lumbosacral junction, offers

Table 4 Radiographic measurements

Parameters	Total patients (n=136)	Patients with hardware related complications (n=34)	Patients with non-hardware related complications† (n=102)	Patients with PI-LL ≥10° (n=77)	Patients with PI-LL <10° (n=59)
Lordosis (°)					
Pre-op	39.9±12.3	40.2±10.0	39.7±14.2	34.3±10.8	47.9±10.1
IM-postop	48.2±12.3	46.8±13.3	49.5±11.3	47.1±13.1	50.0±11.1
Final	44.2±11.6	43.7±11.1	44.7±12.2	42.4±11.2	47.2±12.1
Coronal					
Cobb (°)					
Pre-op	14.6±12.1	14.4±11.4	14.6±12.9	13.6±11.8	16.0±12.7
IM-postop	3.9±4.1	2.3±1.7	4.3±5.3	2.8±2.3	4.3±5.8
Final	3.5±5.3	2.8±2.3	4.8±7.0	3.0±2.6	5.0±7.7
PT (°)					
Pre-op	18.1±9.3	17.5±9.2	18.6±9.4	20.1±8.4	14.3±9.1
IM-postop	16.8±11.1	16.7±11.2	16.9±11.1	19.9±9.3	12.5±12.0
Final	19.0±9.7	18.7±9.0	19.2±10.5	20.9±8.4	16.1±10.1
PI (°)					
Pre-op	49.7±11.7	51.1±9.0	48.5±13.8	52.1±9.5	46.9±13.8
IM-postop	49.2±11.1	50.3±11.5	48±10.9	51.3±10.1	47.7±12.5
Final	49.5±10.8	49.8±10.3	48.9±11.2	51.9±10.9	46.5±10.6
PI-LL (°)					
Pre-op	9.8±12.3	10.9±12.2	8.8±12.3	17.8±11.8	–1.0±12.9
IM-postop	1.5±11.3	4.3±11.8	-1±10.4	4.2±11.1	–2.3±11.6
Final	5.5±11.6	7.4±10.7	3.8±12.3	9.5±11.0	–0.7±12.2

Data are presented as mean ± SD. †, this group includes patients with no surgical complications in addition to patients with non-hardware-related complications (i.e., patients with SSI). PI, pelvic incidence; LL, lumbar lordosis; pre-op, preoperative; IM-postop, immediate postoperative; PT, pelvic tilt; SD, standard deviation; SSI, surgical site infection.

anterior column stability and mechanical load-sharing protection against posterior pedicle screw-rod construct failure or migration. Coronal correction is associated with coronal balance and postural improvement. Nonetheless, sagittal balance reparation is most significantly associated with health quality improvement (23). However, in this study, we found no statistical significance when comparing the final PI-LL mismatch (P=0.41) and final coronal Cobb angle (P=0.33) between patients with hardware complications and patients with no non-hardware-related complications.

According to the authors of this study, the development of cephalad segment disease (9.8%) is multifactorial and includes a combination of the natural progression of disc disease, as well as the mechanical load transfer to the non-fused adjacent segments (23). The rate of PJD in this study (9.8%) falls within the lower range reported by the literature (9.8–31%) when using circumferential MIS (lateral or transforaminal lumber interbody fusion + PPF) to treat ASD in patients with similar characteristics to this study (16,18,19,21). This could be attributed to the use of PPF leading to the preservation of the posterior myofascial envelope which constitutes the posterior tension band (24). However, this was not fully seen in a study by Mummaneni *et al.* (23). Other reasons included using the proper material (5.5 mm titanium rods) and the choice of instrumentation

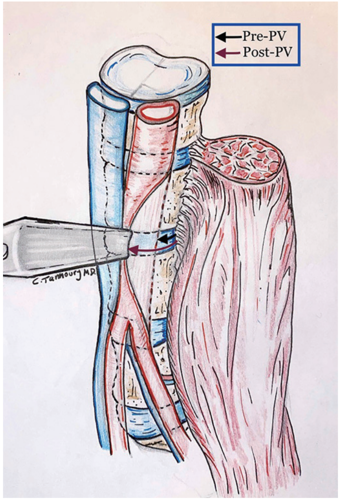

Figure 4 Schematic illustration detailing the vessel manipulation taking place during the MIS-ATP approach along with pre-PV and post-PV windows. Permission use request was granted by Wolters Kluwer Health, Inc. (license: 5726840722341). PV, psoas-vessel; MIS-ATP, minimally invasive surgery antepsoas.

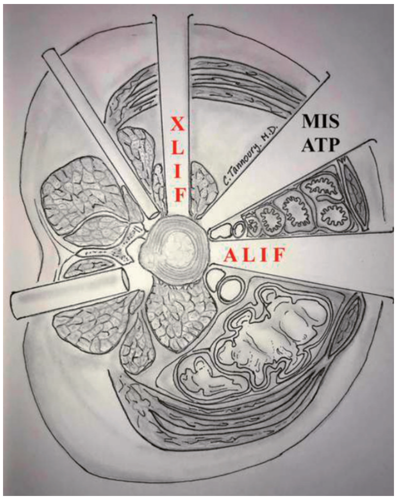

Figure 5 Axial drawing highlighting three different surgical accesses of minimally invasive spine surgeries: ALIF, XLIF, and MIS-ATP. Permission use request was granted by Wolters Kluwer Health, Inc. (license: 5726840722341). MIS-ATP, minimally invasive surgery antepsoas; ALIF, anterior lumbar interbody fusion; XLIF, eXtreme lateral interbody fusion.

(avoiding interbody fusion beyond L1 and using only posterior instrumentation) reduces the stiffness gradient and stress across the proximal junction. Such attributions were similarly addressed by Anand *et al.* (21).

Surgical site infections

Deep hardware infection has been reported (4%) in adult patients treated with spinal fusion (and pelvic fixation) for deformity correction (9). We report a comparable rate of deep infection (4.2%). In our series, only 50% of the SSI were related to the pelvic fixation sites. However, due to the minimally invasive aspect of the percutaneous fixation and soft tissue envelope preservation (MIS performed via interrupted and scattered small incisions, unlike one continuous open midline incision), these infections were localized to only one of the skin incisions and were managed successfully with either local wound care and oral antibiotics (for superficial SSI, 3 patients, 2.1%), or limited surgical site debridement and primary closure with hardware preservation (deep SSI, 6 patients, 4.2%). Besides minimizing complications related to infection, PPF reduces neurological complications, other minor complications, and back pain by minimizing collateral soft tissue dissection compared to the traditional open posterior instrumentation (17).

IS complications

Traditional IS fixation is associated with increased revision rates (27.9%) for either mechanical failure or wound-related complications. Wound infections and hardware prominence were also noted in 25.4% and 18.1% of patients treated with IS fixation, respectively (25). Our series noted lower revision rates (5.6%) due to iliac fixation prominence, pelvic implant mechanical failure, or related pain. Similarly, we noted a reduced incidence of pelvic surgical site infections (2.1%). These can be attributed to numerous protective factors related to the MIS-ATP technique (robust anterior column support and mechanical load sharing construct), limited posterior percutaneous soft tissue stripping, and recessing the sacropelvic implants deep below the posterior bony prominences.

Pseudarthrosis

Many studies reported various pseudarthrosis rates of the instrumented lumbosacral spine. Kim *et al.* reported high nonunion rates (24%) in adult deformity patients treated with long fusions to the sacrum (5). Contrarily, Marques *et al.* reported an overall pseudarthrosis rate of 12% with the combined approach (anterior-posterior) having lower risks of pseudarthrosis in patients with ASD (26). Walker *et al.* conducted a systematic review revealing a pseudarthrosis rate of 9.9% in patients undergoing the ATP (prepsoas) approach (27). Nonunion and implant failure often occur together. As reported by Kebaish *et al.* (4), besides the stiffness and rigidity of the fixation construct, successful arthrodesis is contingent on a sound and effective host biology. If fusion is not achieved in a timely manner, implant failure and related complications are expected. In efforts to improve fusion rate, circumferential fusion with the addition of anterior structural support have been proposed by many authors (9,11,12). This study identified pseudarthrosis based on the Bridwell-Lenke fusion grading system (28). In this cohort, we noted the development of pseudarthrosis in only 3 patients (2.1%), 2 of them needed revision surgery (1.4%). This goes in conjunction with a study that obtained a pseudarthrosis rate of 3.6% in patients undergoing the same surgery as in this study (29). The reduced non-union can be attributed to the ATP's ability to provide ample surgical exposure allowing for generous anterior disc tissue removal, proper endplate preparation, and structural interbody support and reconstruction with graft placement under compression (30). Furthermore, the addition of sacropelvic fixation can be protective at L5–S1 (9). According to a systematic review of complications following a prepsoas approach, our study reports the pseudarthrosis rate on the highest number of ASD patients (n=143) treated with the prepsoas approach (27).

LL restoration and additional benefits/limitations of the MIS-ATP approach

Compared with similar or alternative techniques for long spinal fusions in patients with adult deformity, the MIS-ATP, in our experience, did not rely on an access surgeon and favors anterior fusion with PPF instead of the standard open posterior fusion and instrumentation (15) (*Table 3*). Additionally, the rates of visceral and vascular complications, encountered using the ATP approach coupled with posterior percutaneous pedicle screws and iliac fixation, were scarce (31-33). Although this approach allowed for an average of 73.8% of coronal correction in 94.9% of this cohort, restoring the sagittal should be a higher priority since it is a predictor of quality of life (34). Based on the amount of sagittal correction needed, the MIS-ATP allows for LL restoration through sufficient release of the anterior longitudinal ligament and by that, mitigating the need for an open posterior release or osteotomy (15). LL was restored post-operatively in 70.1% of patients with hypolordosis and PI-LL mismatch <10° achieving a correction of 12.8° post-operatively with a correction 8.1° at final follow-up whereby ALIF increased LL by 6.2°, XLIF increased LL by 9.9°, and transforaminal lumbar interbody fusion (TLIF) decreased LL by 2.1° post-operatively. However, one systematic review that looked into the restoration of LL following minimally invasive TLIF found a postoperative weighted mean increase of LL by 5.2°±5.9° (35-37). Finally, patients who failed to achieve LL correction (PI-LL ≥10°) were at higher risk of developing hardware complications (OR: 2.54; P=0.03). Some limitations regarding the ATP approach and PPF are (I) a significant learning curve and technical expertise. Both senior authors have been performing MIS-ATP for over 15 years; (II) the understanding of long-segment placement of PPF via fluoroscopy; and (III) the added surgical time when performing a staged procedure.

Limitations

This study has several limitations. (I) The retrospective methodology and the associated risks of documentation under-reporting. (II) A lack of control group as patients were considered from a single institution study where different approaches besides the MIS-ATP are rarely used and therefore the outcomes may not be generalizable. (III) The results reported from two spine surgeons who are well experienced in MIS-ATP and percutaneous posterior fixation techniques, therefore the presented outcomes may not reflect other surgeons' experience and learning curves. (IV) Due to lack of standing lateral full-length radiographs of the spine, SVA measurements were not possible, and this should be addressed in future studies. (V) The lack of patient-reported outcomes such as visual analogue scale (VAS) and Oswestry disability index (ODI) scores limits addressing patient function following surgery. (VI) Pseudarthrosis cutoff assessment is mostly preferred at least 1 year following surgery. Surprisingly, no patients in this cohort with only 6 months of follow-up (n=13) had pseudarthrosis, and as a result, they were still included due to their achievement of radiographic bone fusion on CT scan.

Conclusions

In adult patients with spinal deformity warranting long spinal fusions, the MIS-ATP technique, coupled with posterior percutaneous thoraco-lumbar-sacrum-pelvic fixation, allow for anterior column restoration (T12–S1), reliable sagittal alignment and circumferential instrumented fusion, and minimal risks of posterior HF, pseudarthrosis development, and reoperations. Although this technique is technically challenging, with proper training, patients' outcomes can be optimized, and major complications can be mitigated. Future studies warrant larger cohorts with a comparative group using the traditional open-surgical approach.

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Footnote

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Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the institutional review board of Boston University (No. H-36834) and individual consent for this study was waived due to its retrospective nature.

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