The Role of Minimally Invasive Techniques in the Treatment of Adult Spinal Deformity

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KEYWORDS

• Adult spinal deformity • Minimally invasive surgery • Scoliosis

KEY POINTS

- Minimally invasive techniques are feasible options for the treatment of certain subtypes of adult degenerative spinal deformity.
- Careful patient selection for minimally invasive deformity surgery is critical to achieve the best surgical outcome.
- An algorithm is provided to help guide spinal surgeons on the use of minimally invasive techniques for the treatment of patients with degenerative spinal deformity.

INTRODUCTION

Adult degenerative scoliosis is becoming more prevalent in the rapidly growing elderly population. This disease represents a process of degenerative changes of the disks and facets that leads to progressive deformity in both the coronal and sagittal plane. The coronal Cobb angles range from mild (10°–20°) to moderate (20°–40°), with the apex of the curve most frequently located between L2 and L4. The loss of lumbar lordosis (LL) is common and can cause significant sagittal imbalance, which is predictive of a poor quality of life in this patient group.[1] The surgical treatment of adult spinal deformity aims to reduce pain, arrest progression of the deformity, restore sagittal and coronal balance, improve neurologic function, and improve cosmesis.

There are substantial surgical risks for patients with adult degenerative deformity, especially because of their increased age and frequently associated medical comorbidities. Long-segment reconstruction is associated with prolonged operative times under general anesthesia and significant blood loss. The reported complication rates of adult deformity surgery are as high as 41.2%[2] and the rates are even higher in the population older than 75 years,[3] and in the revision setting. A recent multicenter study from the International Spine Study Group[4,5] reviewed a total of 953 adult patients with spinal deformity with minimum 2-year follow-up to identify patients with major perioperative complications. Ninety-nine major complications were observed in 72 patients (7.6%). The most common complications were excessive blood loss (EBL) (>4 L), deep wound infection requiring reexploration of the wound, and pulmonary embolism.

To decrease surgical morbidity and complications, minimally invasive surgery (MIS) approaches

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for the treatment of adult spinal deformity have been proposed. However, not every adult patient with deformity can be managed with MIS. Proper patient selection is the key to successfully treating adult patients with deformity using MIS techniques.

The Rationale of MIS to Treat Adult Degenerative Spinal Deformity

Before using various MIS techniques to treat degenerative scoliosis, several questions need to be clarified. First, can MIS achieve adequate decompression?[6] Second, can instrumentation be placed appropriately with MIS? Third, can solid fusion be established? Fourth, can global coronal and sagittal balance be restored? Recent publications have shed some light on these issues.

Kelleher and colleagues[7] reported a single-surgeon 75-patient consecutive series of minimally invasive bilateral decompression via a unilateral approach at 1 (n = 48) or 2 (n = 27) levels for focal lumbar spinal stenosis. The patients were divided into 4 groups: (A) stenosis with no deformity (n = 22); (B) stenosis with spondylolisthesis only (n = 25); (C) stenosis with scoliosis (n = 16); and (D) stenosis combined with spondylolisthesis and scoliosis (n = 12). The average ages were 68 years and the mean follow-up was 31.8 months. The Oswestry Disability Index (ODI) score improved from 49.1 preoperatively to 23.9 postoperatively. Significant improvement in the ODI score was observed in all 4 subgroups, without intergroup differences. The overall revision surgery rate during a mean 42.8-month postoperative period was 10% and included revision surgery (n = 2) or addition of instrumented fusion (n = 6). The revision rate in the subgroups was (A) 0%; (B) 4%; (C) 25%; and (D) 25%, respectively; and the mean number of months to surgical revision was (B) 25.4, (C) 26.1, and (D) 27.8, respectively. The revision rate was significantly higher in patients with scoliosis than those without. There were 12 patients who had a lateral listhesis (average 13.9%, range, 6%–21%). Six of the 8 revised patients had a lateral listhesis (3 in C and 3 in D, all had >10% listhesis).

Yamada and colleagues[8] reported the outcomes of 46 patients who had microscopic lumbar foraminotomy for degenerative lumbar foraminal stenosis (DLFS). The duration of follow-up was more than 1 year in these patients. Degenerative lumbar scoliosis (DLS) was noted in 26 of the patients, whereas 20 patients were in the non-DLS group. Overall, the Japanese Orthopaedic Association (JOA) scores improved from 13.8 to 21.9 postoperatively. The leg pain was reduced in 44 patients (95.7%) immediately after surgery but recurred in 9 patients (19.6%). The leg pain recurred in 8 (30.8%) of the patients with DLS compared with 1 (5%) of the non-DLS group ($P = .027$). Also, the outcome was good or excellent for 46% of the patients with DLS compared with 80% of the non-DLS group ($P = .029$). Amongst the patients with DLS in whom the difference between standing and supine Cobb angle was less than 3°, 70% had good or excellent outcome and there was no recurrence of leg pain. This result was better than in the patients with DLS with Cobb angle difference of 3° or more; 50% of these patients had recurrent radiculopathy, and only 32% had good or excellent outcomes. Patients with recurrent radiculopathy had significantly higher preoperative Cobb angles than those without recurrence (17.8 ± 3.2 vs 13.8 ± 4.1; $P = .007$).

Anand and colleagues[9] reported 28 patients treated with 3 or more levels of minimally invasive lateral transpsoas interbody fusion (LIF) and percutaneous pedicle screw (PPS) fixation, with a mean age of 67.7 years and mean follow-up time of 22 months. Mean intraoperative blood loss was of 500 mL for both stages, and the operative times were a mean of 500 minutes. The visual analogue scale (VAS), treatment intensity scale, 36-Item Short Form Health Survey, and ODI scores at 1 year were statistically better than preoperative values. The mean coronal Cobb angles were 22° preoperatively and 7.5° postoperatively, but the investigators did not report results of sagittal balance correction. All patients had a solid fusion assessed by plain radiographs at 1 year. However, complications were noted in 23 patients, mostly transient dysesthesia (17/23) related to the LIF approach. The investigators also reported 2 transient quadriceps palsies, 1 retrocapsular renal hematoma, and 1 cerebellar hemorrhage in this cohort.

Tormenti and colleagues[10] reported their retrospective review of 8 cases performed with a combined anterior LIF and open posterior fixation and compared this cohort with 4 cases who underwent posterior-only open surgery. The mean preoperative and postoperative coronal Cobb angles were 39° and 13°, respectively, in the LIF group versus 19° and 11°, respectively, in the posterior-approach-only group. One case of cecal perforation during the anterior approach was reported in this series. The investigators also reported 6 cases of sensory lower extremity dysesthesias as well as 2 cases of lower extremity motor dysfunction after the lateral approach. In most cases, these neurologic issues resolved over several months. The investigators also reported 1 case of infection and meningitis, 1 case of ileus, 1 case of pleural effusion, and 1 patient who had a pulmonary embolus after surgery.

There were no pseudarthrosis or instrumentation failures. The investigators did not report sagittal balance parameters.

Dakwar and colleagues[11] retrospectively reviewed 25 adult patients with degenerative deformity who underwent anterior reconstruction with LIF for 3 or more levels with a mean follow-up of 11 months. The mean intraoperative blood loss was 53 mL per level, with a mean length of stay of 6.2 days. VAS scores and ODI scores improved significantly postoperatively. Complications included 3 cases of transient postoperative anterior thigh numbness, 1 case of rhabdomyolysis requiring temporary hemodialysis, 1 case of implant failure, and 1 case of asymptomatic subsidence. One-third of their cases failed to restore sagittal balance. Reported perioperative complications included 1 patient with rhabdomyolysis requiring temporary hemodialysis, 1 patient with implant subsidence, and 1 patient with hardware failure. In addition, 3 patients (12%) experienced transient postoperative anterior thigh numbness in the distribution of the anterior femoral cutaneous nerve after the LIF procedure.

Wang and Mummaneni[12] retrospectively reviewed 23 patients with thoracolumbar deformity treated with minimally invasive approaches. The mean age was 64.4 years, with a mean follow-up of 13.4 months. The mean blood loss was 477 mL. The coronal Cobb angles improved from 31.4° preoperatively to 11.5° postoperatively. The LL improved from 37.4° preoperatively to 47.5° postoperatively. All of the 16 patients achieved solid fusion at the levels of interbody fusion. Of the 7 cases without use of interbody fusion at every level, 2 patients had pseudarthrosis. Seven patients developed thigh dysesthesia or numbness on the side of the LIF. All of these cases recovered except for 1 patient who had thigh numbness and quadriceps weakness that persisted. Other complications included 1 patient with postoperative atrial fibrillation, 1 case of pneumothorax requiring a chest tube, 1 cerebrospinal fluid (CSF) leak, and 1 patient who needed reoperation for S1 screw pull-out.

Isaacs and colleagues[13] performed a prospective nonrandomized observational study of 107 adult patients with deformity with mean age of 68.4 years who were treated with LIF alone (24.3%) or LIF with either open or percutaneous posterior fixation (75.7%). The mean operative time was 177.9 minutes. A total of 62.5% of patients had a recorded EBL of less than 100 mL and only 8.4% had greater than 300 mL EBL. The overall complication rate was 24.3%. These investigators found that the patients undergoing MIS-only procedures (LIF stand alone or with percutaneous pedicle screws) had significantly lower complications (9% had 1 or more major complications) than those undergoing combined MIS LIF procedures with posterior open pedicle screw fixation procedures (20.7% had 1 or more major complications). The most common major surgical complications were posterior wound infections (3 patients who had open posterior surgery) and postoperative motor deficits (7 cases of persistent motor weakness or having 2 grades decrease in motor strength after LIF procedures). The investigators did not report the preoperative and postoperative sagittal balance parameters as well as fusion status.

Scheufler and colleagues[14,15] reviewed 30 prospectively collected adult patients with degenerative deformity who were treated with mini-open transforaminal lumbar interbody fusion (TLIF) and computed tomography (CT)-guided PPS with an average of 19 months' follow-up. The mean age was 73.2 years. In the 30 patients, a total of 179 segments were fused, among which 134 segments had a TLIF. Mean LL and coronal Cobb angles correction were 44.8° ± 10.7° and 31.7° ± 13.7°, respectively. Mean LL increased from 8.8° ± 8.9° to –36° ± 6.9°, and sagittal vertical axis was reduced from 31.6 ± 15.2 to 8 ± 8.4 mm. Solid fusion was confirmed with CT scan in 90% of the instrumented segments at 18 months. The rate of major and minor complications was 23.4% and 59.9%, respectively. The fusion was not extended to the pelvis, and 2 patients developed symptomatic lumbosacral pseudarthrosis, mandating extension of fusion to the pelvis.

Acosta and colleagues[16] retrospectively evaluated the changes in the coronal and sagittal plane after LIF for the treatment of degenerative lumbar disease in 36 patients. Of this cohort, only 8 patients had degenerative scoliosis; the mean regional lumbar coronal Cobb angles improved significantly from 21.4° preoperatively to 9.7° postoperatively. The mean global coronal alignment was 19.1 mm preoperatively and 12.5 mm postoperatively ($P<.05$). In the sagittal plane, the mean segmental Cobb angle measured –5.3° preoperatively and –8.2° postoperatively ($P<.0001$). The mean preoperative and postoperative regional LL was 42.1° and 46.2°, respectively ($P>.05$). The mean global sagittal alignment was 41.5 mm preoperatively and 42.4 mm postoperatively ($P = .7$). The postoperative ODI and VAS scores improved significantly. However, the fusion status was not reported.

Mundis and colleagues[17] performed a literature review on minimally invasive lateral approaches for interbody fusion to treat degenerative spinal deformity. Both patient-centered outcomes and objective radiographic parameters showed significant improvement in most studies. The complications rates varied between studies, but the major complications were low. Thigh dysesthesia was the most commonly reported complication associated with LIF but was transient in most cases. The investigators concluded that the minimally invasive lateral approach was an effective surgical strategy for adult degenerative deformity.

Berjano and Larmatina[18] also reviewed the current literature for minimally invasive lateral approaches in the treatment of adult deformity, and they proposed a classification of adult lumbar deformity to guide formulation of a surgical strategy for LIF use.

From these published articles, it can be surmised that (1) decompression can be achieved with minimally invasive approaches for a subset of adult deformity cases (because the ODI and VAS are regarded as the surrogates for extent of decompression)[6]; (2) instrumentation can be safely placed with minimally invasive approaches; (3) LIF is effective in treating the coronal deformity (however, restoring the sagittal plane remains an issue); (4) pseudarthrosis is problematic in cases with posterolateral MIS fusion without interbody support; (5) the complication profile of LIF remains to be determined on a large scale, with temporary sensory deficits and transient leg weakness being most common. Because these deficits are approach-related and mostly transient, the question remains whether these temporary neurological changes should be considered as approach related temporary morbidity or as complications.

PATIENT EVALUATION

Physical Examination

A detailed neurologic examination, including muscle power, reflexes, sensory testing, and gait testing, is necessary for patients with spinal deformity. Any degree of shoulder or pelvic asymmetry as well as pelvic obliquity and leg length discrepancy are evaluated and noted. The patients are assessed for any local tenderness in the facets, trochanters, or sacroiliac joints. The range of motion in hip and knee joints is evaluated to identify any contracture.

Radiographic Studies

Patients with adult deformity usually seek medical attention because of radicular leg or back pain, rather than the magnitude of the deformity itself.[19] It is important to identify whether the nature of the pain is radicular, axial, or combined. For pure radicular pain, it is important to confirm that the pain is congruent with the foraminal stenosis on imaging. It is also important to clarify if the stenosis is central, paracentral (lateral recess), foraminal, or extraforaminal. Axial back pain often originates from advanced disk or facet degeneration, worsening subluxation or listhesis (instability), or muscle fatigue from deformity (sagittal or coronal imbalance). It is important to evaluate the dynamic flexion and extension radiographs to identify any instability. The sagittal and coronal balance is assessed on 91.44-cm (36-in) radiographs taken with patients in the standing position with their hips and knees fully extended. This positioning is particularly important in minimally invasive versus open approach planning because it helps the surgeon decide whether an osteotomy is needed for fixed sagittal imbalance to restore the sagittal vertebral axis (SVA) to within 5 cm. Spinopelvic parameters (LL, pelvic incidence [PI], pelvic tilt, and sacral slope) should be assessed for appropriate preoperative planning. The PI and pelvic tilt should be measured. The pelvic tilt is a compensatory parameter that can be altered by patients in an attempt to realign their SVA, but there is a limit to this compensation. The PI, on the other hand, is a fixed parameter that cannot be varied. The surgeon should pay close attention to the parameters of the spinopelvic region, including mismatch of the LL to the PI. Ideally, LL should match the PI $\pm$ 10°. This strategy is important in planning any degree of balance correction necessary to alleviate the patient's symptoms, because sagittal balance correction has been associated with improved clinical outcomes in patients undergoing scoliosis surgery.[20–22]

Magnetic resonance imaging (MRI) is essential in evaluating the location and severity of neural element compression, the degree of disk degeneration, and also any anatomic variations that may hinder certain approaches. Special attention must be paid to the location of the psoas, particularly at L4 to L5 if an LIF is to be used. When the psoas lies more anterior, consideration should be given to an alternate approach. An anterior location of the psoas relative to the vertebral body indicates a narrower corridor for retractor placement and interbody work, because the neural elements similarly lie more anteriorly. It is also important to appreciate the location of the vasculature (iliac vessels, vena cava, and aorta) and their relationship to a rotated lumbar spine.[23] Identification of the position of other retroperitoneal structures is important, including the descending colon on the left side and the kidneys.

CT can be used as a valuable adjunctive tool in evaluating bony anatomy and the three-dimensional anatomy of the spinal deformity, especially in more severe cases. The information gained can also be used to plan the proper diameter and length of the pedicle screws. In patients who have cardiac pacemakers or other MRI-incompatible metal implants, a CT myelogram is the study of choice to evaluate both bony and neural/soft tissue anatomy.

To further elucidate the pain generators, provocative testing such as facet and nerve root blocks can be of value to the deformity surgeon.

MINIMALLY INVASIVE FIXATION/FUSION TECHNIQUES

LIF

The LIF technique begins with preoperative evaluation of the lumbar spine on MRI and CT, when available. Special note is taken regarding the position of the psoas and the location of the great vessels, as well as their bifurcation. Contraindications for this approach include previous retroperitoneal dissection, unfavorable anatomy (including anterior position of the psoas on axial MRI at L4–5), the radiographic appearance of adherent vasculature, previous pyogenic kidney infection or retroperitoneal infection. The decision regarding the side of the approach is dependent on the curve type. Our preference is to approach the spine on the concavity; however, the convex approach may be technically less challenging because the spine rotates toward the convexity in some cases of scoliosis. When approaching the convex side, the release is performed directly over the apex of the curve, and it is possible to perform 3 to 4 levels of LIF through a single skin incision.

The patient is positioned in the lateral position after the appropriate neuromonitoring leads are placed. An axillary roll is used and the peroneal nerve is supported on the down side. The hips and knees are flexed as much as possible to place the psoas under as little tension as possible. The patient is then secured to the operating table with tape and a gentle flexion of the operating table is performed; however, care is taken not to overbreak the table to avoid excess tension on the psoas.

Positioning is confirmed with fluoroscopy in both the anteroposterior (AP) and lateral planes. Because the spine is scoliotic, only 1 vertebra can be perfectly fluoroscopically aligned and imaged at a time, and it is therefore recommended to start imaging the caudal vertebrae. The procedure cannot be initiated until the fluoroscopic views are orthogonal in the AP and lateral plane.

The approach to the spine is a retroperitoneal transpsoas approach. Access can be obtained through 1 or 2 skin incisions. The first incision is located directly over the disk space and the second a finger length posterior to the first and is used as a direct access point to the retroperitoneal space. Using the first incision, dissection is carried bluntly through the abdominal musculature until the fascia is reached. If a second incision is used, the initial dilator is then placed through the first incision and guided to the retroperitoneum via the second incision. The psoas is easily palpable as well as the transverse process, confirming the position in the retroperitoneum. Then, using biplanar fluoroscopy and directional electromyographic (EMG) testing on the initial dilator, the dilator is placed through the psoas onto the disk space and secured with a guidewire. Sequential dilation is performed followed by placement of the retractor, which is secured to the operating table. Then AP and lateral images are used to confirm position of the working corridor.

Next, an 8-step process for disk preparation is performed. First, a knife is used to make an annulotomy, a pituitary rongeur is used to remove the disk material, and next a Cobb elevator is used to dissect the cartilage off both end plates and to gently release the contralateral annulus. The pituitary rongeur is again used to remove excess disk; however, one should not devote too much time to this step to improve efficiency. A 16-mm-long box cutter is then used to further open up the disk space and remove excess disk. Care should be taken to avoid placement of the box cutter too anteriorly to avoid inadvertent removal of the anterior longitudinal ligament. Lateral fluoroscopy is used to ensure the location of the passage of the box cutter. Next, trials are used to pick the appropriate height and width of the interbody cages. The investigators prefer to use cages long enough to slightly overlie the lateral aspects of the vertebral bodies to avoid complications such as subsidence and to allow for the most load-sharing environment. While the cage is being prepared (filled with allograft or other fusion substance) on the back table, the endplates are prepared with stirrup curettes to ensure a good bleeding bony endplate surface exists for bony ingrowth. The implant is then placed into the disk space under fluoroscopic guidance.

Neuromonitoring, specifically directional EMG testing, is integral to the safety of this procedure. It is vital to have a clear neurologic path through the psoas muscle to access the spine using directional EMG to identify the nerves at risk at each level being worked on. During the remainder of the procedure, free running EMG allows identification of any abnormal activity. Long retractor times are not favorable because the static/rigid retraction of these peripheral nerves within the psoas muscle can result in paresthesias and neuropraxia.

Posterior Mini-Open TLIF and Mini-Open Pedicle Screw Fixation

The pelvic rim obstructs the lateral access to the L5/S1 disk space. Mini-open TLIF is an option to achieve a solid interbody fusion for this level.

Table 1
Summary of Prior MIS Deformity Surgery Publications

Reference	Patients/ Procedures	Outcomes				Complications		Remarks
Acosta et al 2011[16]	36 patients with lumbar degenerative disease	Fusion rate: N/A				N/A		No report fusion rates
	LIF + posterior percutaneous screw	Clinical	Pre	Post	*P*<.05			Mean f/u: not reported
		VAS	7.7	2.9				
		ODI	43	21				
		Coronal plane correction						
		Segmental Cobb	4.5°	1.5°	*P*<.0001			
		Regional lumbar Cobb	7.6°	3.6°	*P*<.0001			
		Sagittal plane correction						
		Segmental Cobb	5.3°	8.2°	*P*>.05			
		Regional lumbar lordosis	42.1°	46.2°	*P* = .7			
		Global sagittal alignment (mm)	41.5	42.4				
Anand et al 2010[9]	28 adult scoliosis patients/(LIF ± AxiaLIF) plus post percutaneous screw	Fusion 1 y: 100%				23 complications:		Fusion is determined by static radiograph and CT in 21 patients
	(LIF > 3 levels)	Surgical data				Transient dysarthria	17	Mean f/u: 22 mo
		EBL				Quadriceps palsy	2	
		Anterior procedures: 241 mL				Retrocapsular renal hematoma	1	
		Posterior procedures: 231 mL				Cerebellar hemorrhage	1	
		Operating room times				Screw prominence	1	
		Anterior 232 min				Asymptomatic proximal screw fracture	1	
		Posterior 248 min						
		Cobb angles	Preoperative	22.3°	*P*<.05			
			Postoperative	7.47°	*P*<.05			
		Clinical	Preoperative	Postoperative				
		VAS	7.05	3.03				
		TIS	53.5	25.88				
		SF-36	55.73	61.50				
		ODI	39.13	7.00				

Dakwar et al 2010[11]	25 adult patients with degenerative deformity		Fusion rate: 100% for those with f/u >6 mo (n = 20) EBL: 53 mL/level OP time: 108 min/level				Rhabdomyolysis	1	Fusion is determined by CT and flexion/extension radiograph
	LIF only	2	Clinical	Preoperative	Postoperative	*P*: N/A	Subsidence	11	
	LIF + LP	15	VAS	8.1	2.4		Hardware failure	1	Mean f/u: 11 mo
	LIF + PSF	7					Thigh numbness (transient)	3	
	LIF + PSF + LP	1	ODI	53.6	29.9				
Isaacs et al 2010[13]	107 adult patients with degenerative deformity		Fusion rate: N/A EBL: <100 mL in 62.5% >300 mL in 8.4%				13 (12.1%) patients experienced 14 major complications		Focused on complications within 6 wk postoperatively
	XLIF stand alone	20	OP times: 177.9 min per surgery (57.9 min per interbody fusion level)				Of 36 patients (33.6%) with some evidence of weakness after surgery, 29 had isolated proximal hip weakness (25 patients are transient weakness)		
	XLIF + LF	6	Patients with entirely minimally invasive procedures had significantly lower incidence of having any complication than patients with open posterior instrumentation (19.2% vs 37.9%) (*P* = .0450).				7 cases had weakness last longer than 6 mo or was decreased by 2 grades at any time point		
	XLIF with open PSF	29							
	XLIF with MIS PSF	52							
Kelleher et al 2010[7]	75 consecutive patients who underwent MIS decompression for focal lumbar spinal stenosis		ODI	Pre	Post	P<.05	The revision rate for patient with scoliosis (C + D) was significant (*P* = .0035) compared with those without (A + B)		Mean postoperative f-u: 31.8 mo
	(A) Stenosis with no deformity (n = 22)		A	48%	18.7%		Six of the 8 revised patients had a preoperative lateral (rotatory) listhesis (3 in C and 3 in D)		
	(B) Stenosis with spondylolisthesis only (n = 25;		B	48%	24.6%				
	(C) Stenosis with scoliosis (n = 16;		C	50.7%	31.5%				
	(D) Stenosis combined with spondylolisthesis and scoliosis (n = 12)		D	53%	22%				
			Revision rates (overall: 10%) (A) 0%; (B) 4%; (C) 25%;(D) 25%;						

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Table 1
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Reference	Patients/ Procedures	Outcomes				Complications		Remarks
Scheufler et al 2010[14,15]	30 patients with degenerative lumbar kyphoscoliosis	Fusion rates: 90% for instrumented segment by CT criteria				Major complication rates: 23.4%		Mean f-u was 19.6 mo
		Clinical	Preoperative	12 mo postoperative	P<.05	Minor complication rates: 59.9%		
		VAS	7.5	2.63				
	Mini-open TLIF and CT-guided PPS (179 segments were fused, among which 134 segment had a TLIF)	SF12V2PCS	20.2	34.6				
		ODI	57.2	24.8				
		Coronal plane correction						
		Cobb angles	42°	10.3°				
		Coronal balance (mm)	n/a	3.7				
		Sagittal plane correction						
		LL	8.8 ± 8.9°	−36 ± 6.9°				
		SVA (mm)	31.6 ± 15.2	8 ± 8.4				
Tormenti et al 2010[10]	8 patients XLIF + open PSF	Fusion rate: N/A			*P*<.001	XLIF + PSF		Mean f-u: ~11 mo
		XLIF + PSF	Preoperative	Postoperative		Motor radiculopathy	2	
	4 patients TLIF/ PLIF + open PSF	Cobb angles	38.5°	10.0°		Thigh paresthesia	6	
		AVT (cm)	3.6	1.8		Cecal perforation	1	
		Lumbar Lordosis	47.3°	40.4°		Pleural effusion	2	
		VAS	8.8	3.5		Pulmonary embolism	1	
		PLIF/TLIF + PSF				Durotomy	1	
		Cobb angles	19°	11°		PLIF/TLIF + PSF:		
		AVT (cm)	2.2	1.1		*Clostridium difficile* colitis	1	
		LL	30°	37.7°		Durotomy	1	
		VAS	9.5	4		Junctional kyphosis	1	

Wang and Mummaneni 2010[12]	23 patients with thoracolumbar deformity	Fusion rate: 91.3%				Postoperative thigh numbness	1	Mean f-u: 13.4 mo
		Mean 3.7 intersegmental levels/patient				CSF leak 1	1	
		EBL: 477 mL				Large blood loss	1	
	Mini-open LIF + PPS	OP times: 401 min				Screw pull-out	1	
			Preoperative	Postoperative		Pneumothorax	1	
		Cobb angles	31.4°	10.3°		New-onset atrial fibrillation	1	
		LL	34.7°	47.5°				
		VAS leg pain	4.35	1.57				
		VAS axial back pain	7.30	3.35				
Yamada et al 2011[8]	46 patients with DLFS were treated with microscopic lumbar foraminotomy	Clinical	Pre	Post		Recurrent leg pain: group 1 (30.8%) vs group 2 (5%) $P = .029$		Mean f-u: 21.9 mo
		JOA	13.8	21.9				
		JOA score improvement ratio:			$P = .027$			
		Group 1 < group 2			$P = .007$			
	Group 1: Cobb angle ≥10° n = 26	Preoperative Cobb angle and Cobb angle difference between supine and standing position are significantly higher in patients with recurrent leg pain than those without			$P = .006$			
		Subgroup analysis of group 1:						
		Cobb angle difference <3°:						
	Group 2: Cobb angle <10° n = 20	No recurrence; 70% showed good or excellent results						
		Cobb angle difference ≥3°:						
		50% patients had recurrence; 23% had good or excellent results						

Abbreviations: AVT, apical vertebral translation; DLFS, degenerative lumbar foraminal stenosis; f-u, follow-up; JOA, Japanese Orthopaedic Association; LIF, Lateral Interbody Fusion; LL, Lumbar Lordosis; LP, lateral plate; N/A, not applicable; ODI, Oswestry Disability Index; PSF, pedicle screw fixation; SF-12V2 PCS, 12-Item Short Form Health Survey Version 2 physical component summary; SF-36, 36-Item Short Form Health Survey; SVA, sagittal vertical axis; TIS, Treatment intensity scale; TLIF, transforaminal lumbar interbody fusion; VAS, Visual Analogue Scale; XLIF, extreme lateral interbody fusion.

The patient is positioned prone on a Jackson table in reverse Trendelenburg position to help provide better visualization of the L5/S1 disk space.

For 1 or 2 level cases, the Wiltse plane incision location is identified by AP fluoroscopy to identify the lateral aspect of the pedicles and marked on the skin. For 3 or more levels, a midline skin incision and then a paramedian fascial incision are used. The fascial incisions are made at the outside margins of the pedicles (3–4 cm laterally to midline). After the skin and fasciae are incised, the Wiltse plane between multifidus and longissimus muscles is developed bluntly and serially enlarged with sequential dilators. The expandable tubular retractor is inserted. The optimal position and angle of the retractor are confirmed by lateral fluoroscopy.

The lateral facet complex, the transverse process, and pars interarticularis are identified and exposed with Bovie electrocautery and dissecting curettes. The pedicle screw entry point is located at the junction of midpoint of transverse process with the lateral aspect of the superior articulating facet in the mini-open technique. After decorticating the entry point with a high-speed drill, a gear shift is used to navigate through the cancellous bone of the pedicle into the vertebral body. A pedicle marker is placed into the hole. The marker provides an anatomic visual cue during the facetectomy and diskectomy. The same procedure is repeated for the remaining planned pedicle instrumentation levels. The pedicle screws are placed after completion of the diskectomy, end plate preparation, and insertion of the interbody cage.

Facetectomy and foraminotomy are performed with a drill and chisel to expose the disk space. The diskectomy and end plate preparation are performed efficiently with end plate shaver, pituitary rongeurs, and curettes. It is critical to remove the cartilaginous end plate without violating the bony end plate, to prevent cage subsidence. Next, an appropriately sized cage is selected based on interbody dilators used during serial dilation of the disk space. Autograft is packed into the disk space before cage insertion using a bone funnel. Next, the interbody cage is packed with autograft and implanted into the disk space.

Decompression of the neural elements is performed after cage insertion. The expandable retractor may need to be realigned medially onto the ipsilateral hemilamina to perform decompression. The contralateral decompression can be achieved by aligning the retractor even more medially to visualize and thin the contralateral lamina (so called ipsicontra decompression). The ligamentum flavum can be removed after all the drill work is finished to decrease the risk of dural tear.

The appropriate-sized pedicle screw is inserted into the formerly prepared bony entry points. EMG stimulation on the pedicle screw can help verify the integrity of the cortical bone around the pedicle. The bone graft is placed in between the transverse process before the rods are secured to the pedicle screw heads.[24,25]

Percutaneous Pedicle Screw Fixation

The pedicle screws may be inserted percutaneously on the contralateral side of the TLIF approach or to supplementally fixate a lateral interbody fusion. The true AP fluoroscopic view of each particular vertebral body intended for fixation is critical for accurate screw insertion. A true AP image can be identified by the single radiopaque shadow of the upper end plate, and the properly aligned image can be confirmed by the centrally located spinous process between the pedicles. With the true AP image, the trajectory to reach the pedicle can be achieved by placing a Jamshidi needle over the skin and adjusting the position to be in line with the centers of the bilateral pedicles of interest. Skin incisions are marked 1 cm lateral to the AP superimposed position of the pedicle to allow for a lateral to medial screw trajectory. After the skin and fasciae are incised, the tract to the transverse process can be developed using index finger blunt dissection. A Jamshidi needle is inserted and docked at the base of the transverse process, as mentioned earlier. An AP view is obtained, and the needle is adjusted to position its tip over the lateral border of the pedicle (3 o'clock for left pedicle/9 o'clock for right). After confirming the ideal entry point, the needle is tapped a few millimeters into the pedicle after making a 2-cm mark on the shaft. The shaft of the needle must be aligned parallel to the end plate on AP view. The Jamshidi needle is tapped gently under fluoroscopy to advance 2 cm in depth. The tip of the needle is now at the junction of the pedicle with the vertebral body. A true AP view is obtained to confirm that the tip of the needle is not medial to the medial shadow of the pedicle. The obturator is removed and a blunt-tipped guidewire is introduced through the needle into the cancellous bone. The Jamshidi needle shaft is removed with special attention to hold the guidewire in place. The pedicle is then tapped with a cannulated tap and the cannulated pedicle screw is inserted over the guidewire. Lateral fluoroscopy is taken to ensure proper trajectory for tapping and screw placement.[24,26] Care is taken to prevent K-wire migration through the ventral vertebral body during tapping and screw placement.

ALGORITHM FOR MINIMALLY INVASIVE APPROACHES TO TREATMENT OF ADULT DEGENERATIVE SPINAL DEFORMITY

The main goals for the treatment of adult degenerative spinal deformity are neural element decompression, establishing or maintaining sagittal and coronal global balance, and arthrodesis. Operative interventions require evaluation of the unique needs and goals of each patient. Several classification schemes as well as levels of treatment have been proposed for adult spinal deformity. In 2010, Silva and Lenke[6] published a treatment-level guide to adult degenerative deformity management. In this scheme, the patients who need treatment are classified into 6 treatment levels, based on clinical and radiographic findings. Of the 6 Lenke-Silva treatment levels, treatment levels I to IV could be appropriately treated with current minimally invasive techniques based on published data (**Table 1**).[9,11,12] We have modified the Lenke-Silva paradigm to create an algorithm for the minimally invasive treatment of spinal deformity, which we have termed the MiSLAT (Mummaneni, M. Wang, Silva, Lenke, Amin, Tu) algorithm (**Fig. 1**).[24]

MiSLAT Treatment Level I

Patients with level 1 disease present with symptoms of neurogenic claudication or radiculopathy caused by central, lateral recess or foraminal stenosis. These patients (**Fig. 2**) have minimal back pain and symptoms with regard to their deformity. Radiographically and clinically, there is no sagittal

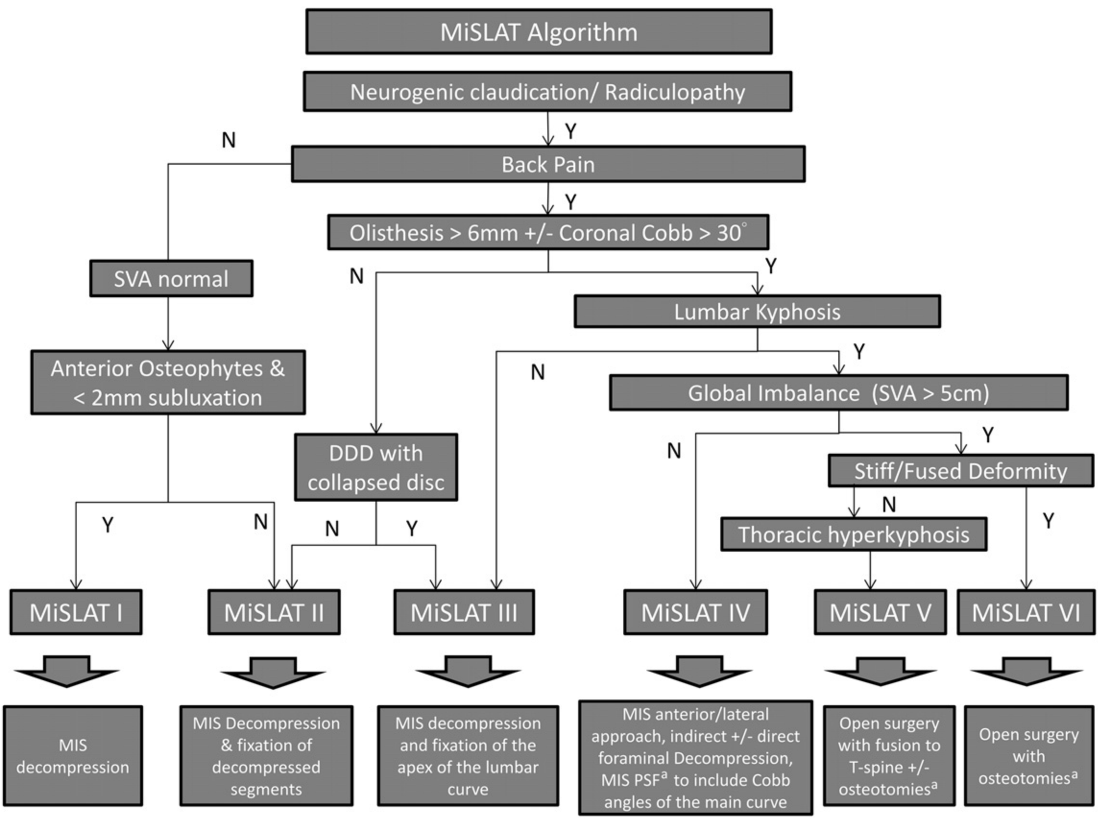

Fig. 1. MiSLAT algorithm for MIS treatment of adult degenerative deformity. MiSLAT I = decompression only; MiSLAT II = decompression and limited pedicle screw fixation of a portion of the coronal curve with posterolateral bone graft or TLIF; MiSLAT III = decompression and pedicle screw fixation of the apex of the lumbar curve with posterolateral bone graft or TLIF/extreme lateral interbody fusion (XLIF)/direct lateral interbody fusion (DLIF); MiSLAT IV = decompression and pedicle screw fixation of the lumbar spine with TLIF/XLIF/DLIF to include Cobb angles of the main curve[a]; MiSLAT V = decompression and pedicle screw fixation and fusion extending into thoracic region for thoracic hyperkyphosis ± osteotomies[a]; MiSLAT VI = correction of thoracolumbar scoliosis with 3-column or multiple-facet osteotomies and multisegmental pedicle fixation and fusion[a]. [a]Iliac screw insertion is suggested for constructs extending longer than L2 to S1. (*Adapted from* Mummaneni PV, Wang MY, Silva FE, et al. Minimally invasive evaluation and treatment for adult degenerative deformity–using the MiSLAT algorithm. In Scoliosis Research Society E-Textbook. Available at: http://etext.srs.org/book/. Accessed August 13, 2012; with permission.)

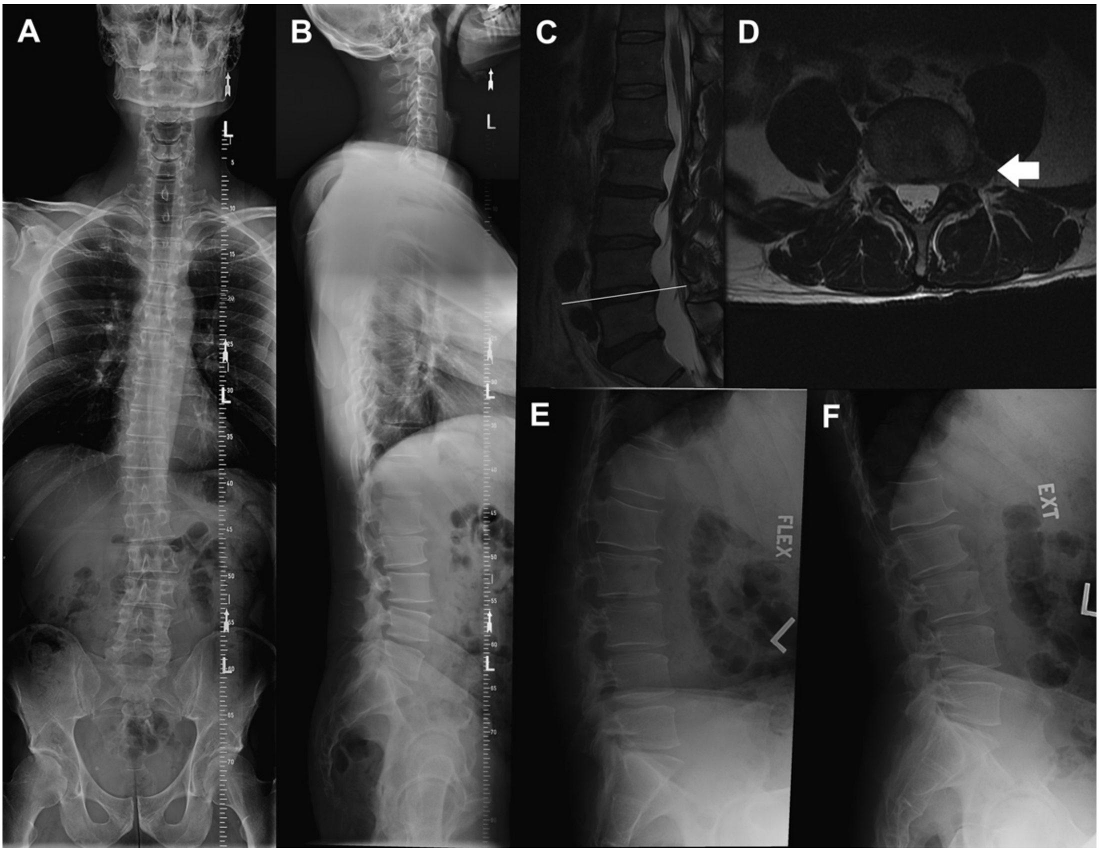

Fig. 2. A 46-year-old man presented with a left leg radiculopathy. He did not have back pain. (*A, B*) 91.44-cm (36-in) radiographs show mild thoracolumbar scoliosis and maintained sagittal balance. (*C, D*) Sagittal and axial T2-weighted MRI reveals a far lateral disk herniation (*arrow*) at the left L4/5 level. (*E, F*) Flexion and extension radiographs did not show any instability. This patient had a minimally invasive far lateral diskectomy without instrumentation (MiSLAT I treatment).

or coronal imbalance. There is no dynamic instability on flexion and extension X-rays. Patients in this treatment level should have subluxation of less than 2 mm, and the curve should be less than 30°. The treatment goal in this group of patients is central canal, lateral recess, and nerve root decompression and not correction of their deformity. Minimally invasive techniques are well suited to this type of decompression. Typically, a tubular retractor is used to perform an ipsilateral hemilaminotomy and foraminotomy. Then, by angling the tubular retractor medially, an undercutting contralateral decompression is also possible (ipsicontra decompression). This type of ipsicontra decompression may be performed at 1 or 2 contiguous levels through 1 small incision. The midline spinous processes and interspinous ligaments are spared.

MiSLAT Treatment Level II

Patients with level II disease (**Fig. 3**) complain of similar neurologic issues as those in level I; however, they have a greater back pain component. Radiographically, there is more than 2 mm of subluxation, Cobb angles are less than 30°, and anterior osteophytes are present, indicating some level of stability. Globally, these patients remain well balanced in the sagittal and coronal plane, with the absence of lumbar kyphosis. Treatment involves decompression of the spine at one or two levels and concomitant focal instrumentation at the area of decompression is recommended to treat dynamic flexion and extension instability. We treat these patients with a minimally invasive decompression and limited instrumented fusion. It is important to understand the context of the limited fusion in light of the given deformity. Ideally, the fusion results in parallel end plates in the coronal plane and restoration of normal lordosis within the segment(s) fused. Fusion can be achieved through MIS or mini-open TLIF or LIF followed by percutaneous pedicle fixation and minimally invasive decompression with tubular retractors, as described earlier. The surgeon may

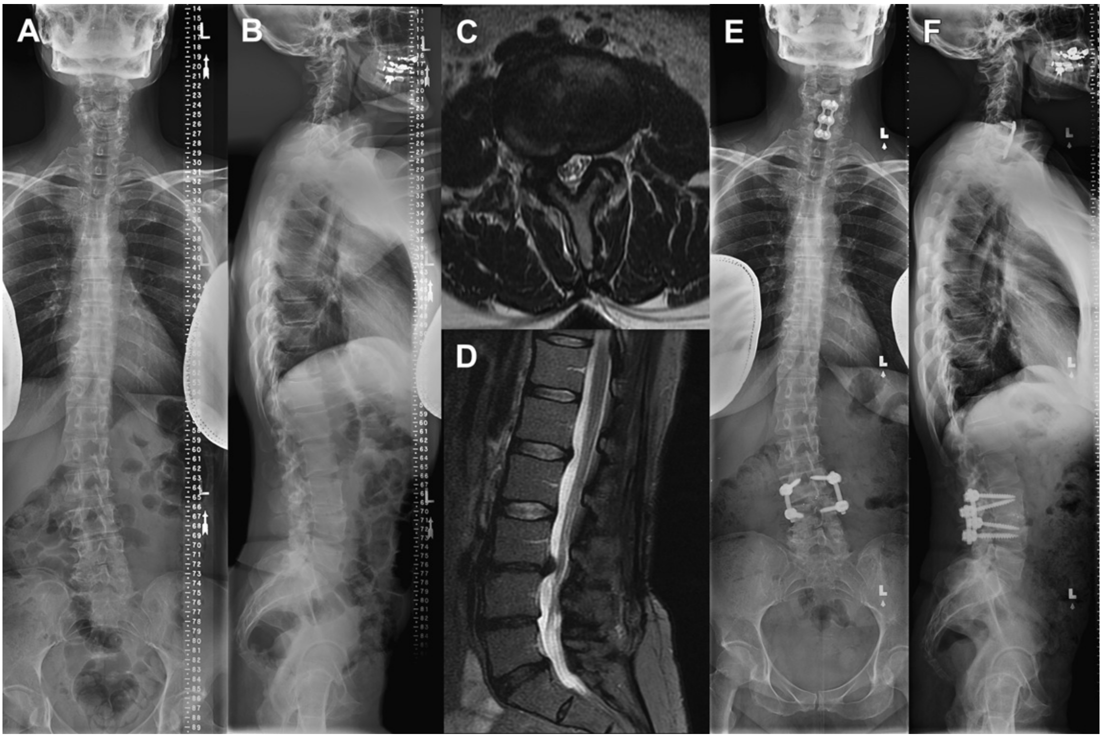

Fig. 3. A 52-year-old woman with radicular right leg pain and back pain. (*A, B*) 91.44-cm (36-in) preoperative radiographs showed a mild lumbar scoliosis (Cobb angle of 16°) and maintained sagittal balance (SVA = 2.0 cm). (*C, D*) T2-weighted axial and sagittal MRI shows a right herniated disk causing lateral recess stenosis at the L3 to 4 level. (*E, F*) Postoperative 91.44-cm (36-in) radiographs after a minimally invasive L3 to 4 TLIF (MiSLAT II treatment).

choose the TLIF or LIF depending on the patient's anatomy (ie, the position of the iliac crest precludes some L4–5 surgeries and L5–S1 cannot be accessed via LIF).

MiSLAT Treatment Level III

Patients with level III disease have a more dominant back pain component to their chief complaint in addition to their neurologic issues. Radiographically, they have more than 2 mm of subluxation/olisthesis, lack anterior bridging osteophytes, and present with Cobb angles greater than 30°. As with level II disease, decompression and fusion are necessary; however, these curve patterns and extent of the deformity usually require fusion beyond the levels involved for the decompression, and typically require fusion of the apex of the lumbar deformity. Minimally invasive techniques are well suited because they achieve the same goals as the open approaches. As with level I, decompression can be achieved at multiple levels through expandable tubular retractors, and, as with treatment level II, instrumentation can be performed via percutaneous or mini-open techniques, and interbody grafting achieved posteriorly via tubular retractors or LIF. In addition, minimally invasive LIF may allow for indirect foraminal decompression by distracting the interbody space and recreating foraminal height.

MiSLAT Treatment Level IV

Patients with level IV disease have claudication-radicular pain, back pain, lumbar hypolordosis/kyphosis and lack anterior osteophytes. The goal of the operative intervention includes decompression, instrumentation, interbody fusion, and correction of the lumbar flat back. Radiographs of these patients show segmental instability and loss of LL, but no significant global imbalance (SVA <5 cm) (**Fig. 4**). As already delineated, decompression, instrumentation, and interbody graft placement and arthrodesis can all be achieved with minimally invasive techniques. Lordotic interbody grafts are placed from the lateral approach before posterior segmental mini-open or percutaneous pedicle screw instrumentation. The lordotic interbody cages not only serve in kyphoscoliosis correction and derotation but also place the pedicles at a more physiologic angle, making the landmarks for percutaneous pedicle

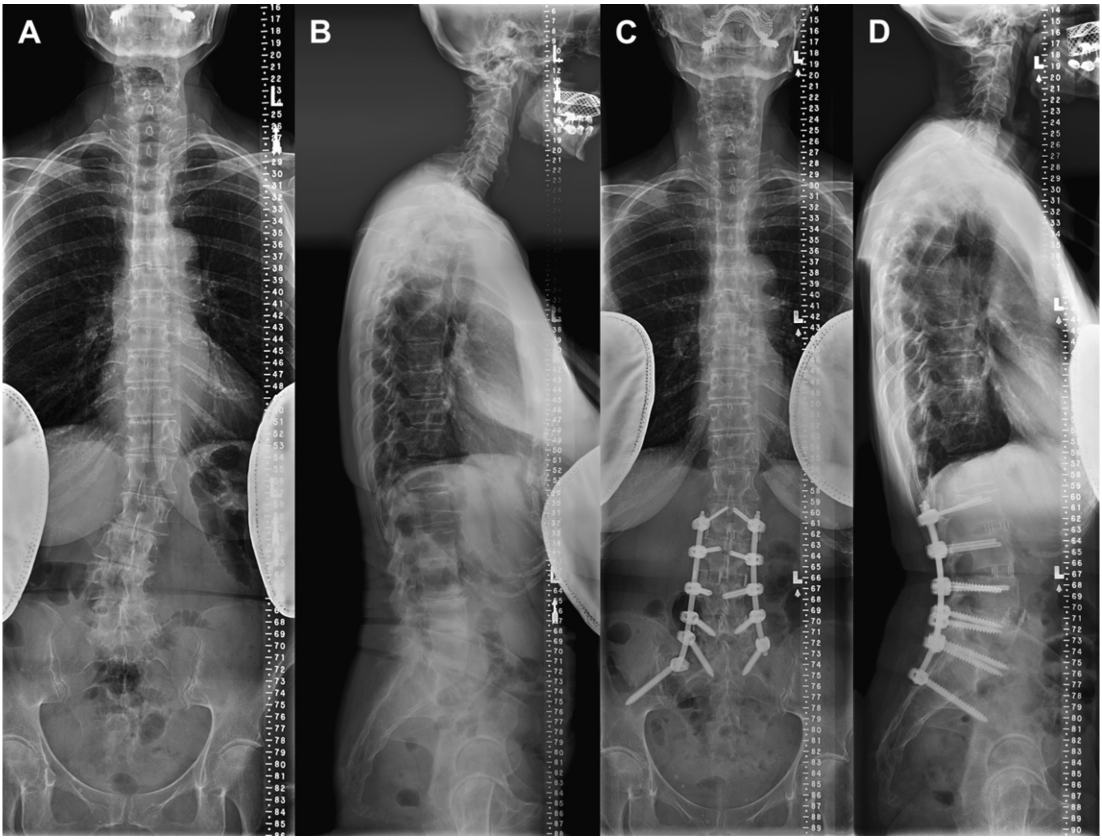

Fig. 4. A 67-year-old woman presented with low back and bilateral radicular leg pain. (*A, B*) Her preoperative 91.44-cm (36-in) radiographs revealed L2 to 3 lateral listhesis, an SVA of 4.3 cm, and a lumbar lordosis of 27°. (*C, D*) Postoperative 91.44-cm (36-in) radiographs after an L2 to L5 LIF and an L2 to the sacrum posterior MIS spinal fusion with a right iliac screw fixation (MiSLAT IV treatment).

screw fixation easier to identify. Particular attention is paid to restoring normal segmental lordosis in the lower levels of correction, particularly at L4 to L5 and L5to S1 (via TLIF or mini-anterior lumbar interbody fusion), because two-thirds of LL comes from these 2 segments. Also, it is important to match the LL to the patient's individual PI ± 10°.[21,27,28] MiSLAT IV treatment involves fixation of the entire spinal deformity, with special attention given to the lumbosacral fractional curve, because it needs to be included in the fusion construct. If the fusion extends to the sacrum, it may also be necessary to place iliac instrumentation long fusions (L2 or above to sacrum) to help achieve a solid fusion at the lumbosacral junction, to avoid sacral insufficiency fractures, and to protect the fixation at S1. Recent advances allow iliac screw fixation via percutaneous minimally invasive techniques.[29] Another option is to place S2-AI screws as described by Kebaish.[30] Alternatively, Anand and colleagues[31] have reported on their use of the presacral minimally invasive approach to provide additional support and avoid pelvic fixation, although the long-term efficacy of this strategy has not yet been elucidated.

MiSLAT levels I to IV include deformity patterns that are amenable to current MIS techniques. Principles of proximal and distal fusion levels established for open surgery are also applicable to minimally invasive deformity surgery, with the exception of the choice of the upper-instrumented vertebrae. Because the soft tissue overlying the spine is preserved with minimally invasive approaches, typical cranial stopping points for multilevel lumbar instrumentation in MiSLAT IV treatments may vary from T10 to L2.

MiSLAT Treatment Levels V and VI

For patients with claudication-radicular symptoms, back pain, lumbar hypolordosis/kyphosis, and global sagittal imbalance (SVA >5 cm), standard open approaches are preferred, because current minimally invasive techniques often do not permit the achievement of the treatment goals (restoration of overall spinal balance). MiSLAT level V treatment (**Fig. 5**), which refers to open surgery with fusion extending to the T-spine with/without osteotomies, is suitable for these patients if they also show thoracic hyperkyphosis. MiSLAT VI treatment (**Fig. 6**), which involves open surgery with various osteotomies, is suitable for those patients with global sagittal imbalance and stiff, decompensated deformities (eg. iatrogenic flat-back syndrome).

Patients with level V disease present with significant coronal and sagittal imbalance in addition to back and leg pain. The deformity remains flexible but extends to the upper thoracic spine and requires thoracic and lumbar realignment to achieve the desired postoperative outcomes. Patients with level VI disease have a fixed deformity such as iatrogenic flatback deformity with over 5 cm of sagittal imbalance, frequently requiring 3-column osteotomy for realignment. Level VI cases do not need fixation to the upper thoracic spine. Because these deformities are more extensive, standard open approaches are preferred, because current minimally invasive techniques do not predictably achieve the intended goals of the surgery. Osteotomies are covered in detail elsewhere in this issue.

Schwab and colleagues[32] recently updated the previous published Scoliosis Research Society (SRS)-Schwab classification to incorporate spinopelvic parameters, which are highly correlated with health-related quality-of-life scores. The classification comprises curve type, which is aimed at describing the relevant coronal aspects of the deformity; and 3 modifiers to characterize sagittal components of the deformity. The interrater and intrarater reliability and interrater agreement for the updated classification are excellent. When it comes to using minimally invasive procedures to treat patients classified with the SRS-Schwab classification, the patients with PI-LL modifier + or ++ (ie, PI-LL value is greater than 20°), or global alignment modifier + or ++ (ie, SVA >40 mm) are typically not suitable for a minimally invasive approach. These patients need more extensive releases or osteotomies to achieve spinopelvic balance.[33]

Recently, the use of a mini-open pedicle subtraction osteotomy (PSO) has been proposed.

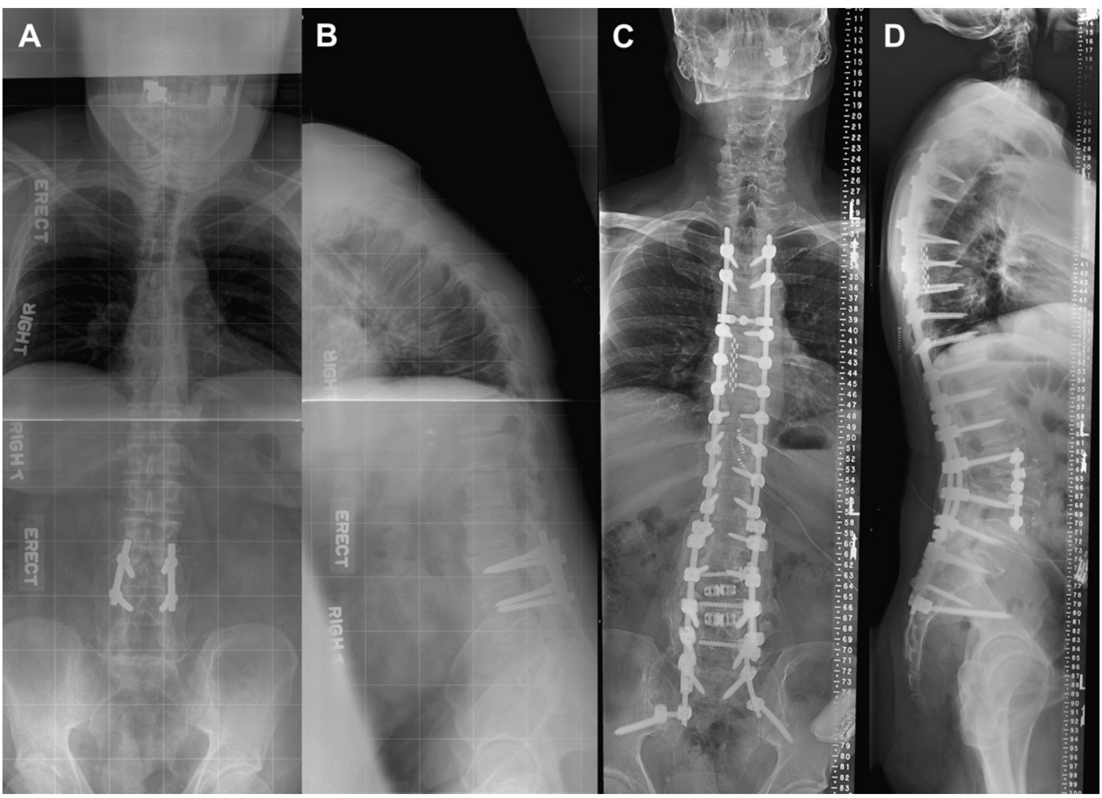

Fig. 5. A 50-year-old man presented with radicular right leg pain, low back pain, and inability to maintain erect posture. (*A, B*) 91.44-cm (36-in) radiographs show severe sagittal imbalance (SVA 21.2 cm) and thoracic hyperkyphosis. (*C, D*) Postoperative 91.44-cm (36-in) radiographs after L3 pedicle subtraction osteotomy, T6 to 8 Smith-Peterson Osteotomy (SPOs), T3-pelvis posterior fusion and staged L2 to 3, 3 to 4 anterior lumbar interbody fusions (MiSLAT V treatment).

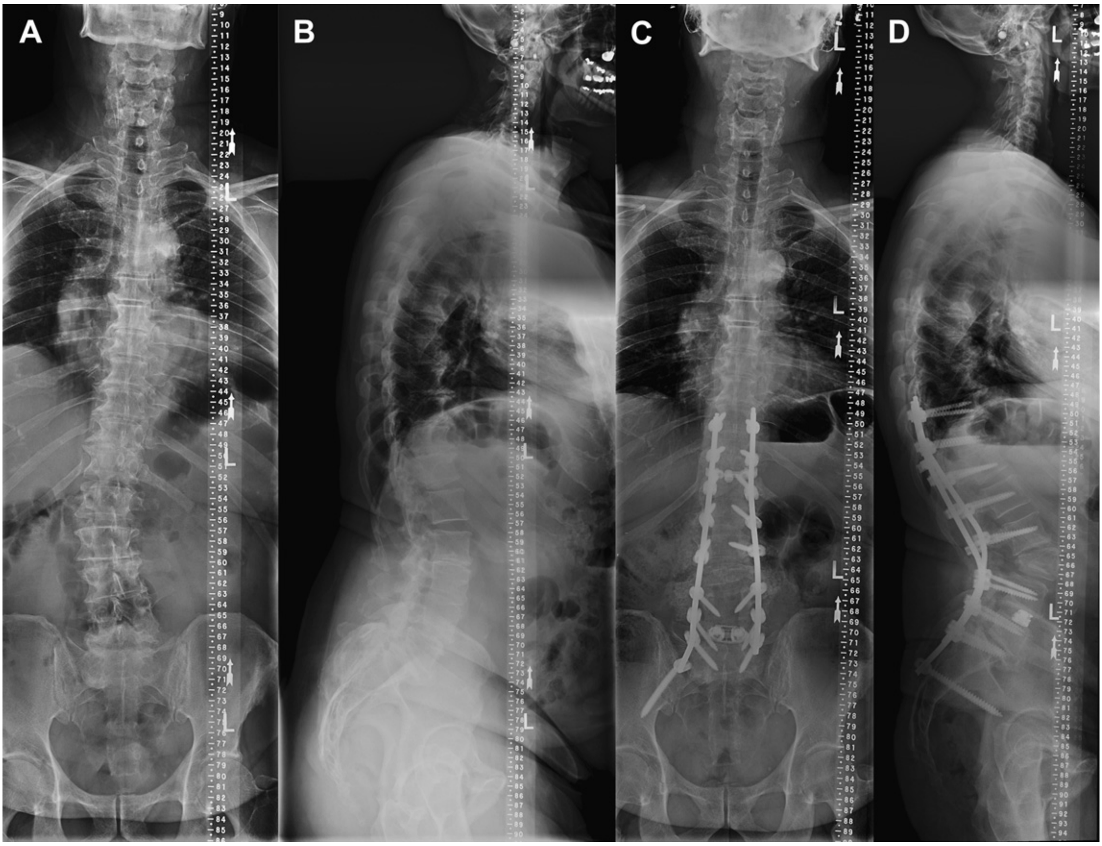

Fig. 6. A 64-year-old man presented with low back pain and inability to stand upright for long. (*A, B*) His 91.44-cm (36-in) radiographs showed significant sagittal imbalance (SVA = 8.5 cm). (*C, D*) Postoperative 91.44-cm (36-in) radiographs after an L3 pedicle subtraction osteotomy with T10 to S1 pedicle screw fixation and extension to right pelvic (MiSLAT VI treatment).

Initial laboratory investigations with cadavers showed the use of bilateral tubular retractors to perform the necessary bone removal.[34] However, in clinical application, the blood loss associated with PSO techniques, the possibility of neural compression during osteotomy closure, and the need for control of the spinal column during deformity correction have limited this MIS application. There is no long-term follow-up on the use of MIS techniques for PSO. We do not use MIS techniques for PSO. We prefer to perform open surgery to complete a PSO.

Rehabilitation and Recovery

Deep vein thrombosis (DVT) prophylaxis is an essential part of postoperative management in patients who have undergone spinal surgery. Sequential compression devices and stockings should be used throughout the postoperative period. Perioperative anticoagulation with low-molecular-weight heparin is mandatory in patients with high risk of thrombosis (excluding those with history of DVT, with acute DVT, having older mechanical valve, or with hypercoagulable status) in addition to the compression stockings. Early mobilization should be encouraged if it is not contraindicated. Rehabilitation is beneficial for patients with focal motor weakness, impairment in motion coordination, and impaired sensory functions.

The length of hospital stay for minimally invasive spinal deformity surgery may be 3 to 5 days, depending on the extent of procedures. Patients can return to regular daily activity in 3 to 4 weeks and are allowed full participation in 3 to 6 months depending on their activities.

CLINICAL RESULTS IN THE LITERATURE

The clinical results of selected references are summarized in **Table 1**.

SUMMARY

Recent advances in minimally invasive access to the spine have empowered spine surgeons to apply these techniques to patients with spinal deformity. However, regardless of technique, it is imperative that the principles of deformity correction are adhered to. These principles include thorough decompression for neurologic symptoms, stabilization of the deformity with pedicle screws, arthrodesis via interbody techniques, and maintenance or correction of the sagittal and coronal global malalignment. We present an established algorithm (MiSLAT) for adult spinal deformity with minimally invasive applications. Our recommendation is to treat levels I to IV with minimally invasive techniques; however, we believe that level V and VI deformities require more traditional open approaches to reliably correct the deformity.

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