

Minimally invasive lateral approach for adult degenerative scoliosis: lessons learned

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Object. Lateral minimally invasive thoracolumbar instrumentation techniques are playing an increasing role in the treatment of adult degenerative scoliosis. However, there is a paucity of data in determining the ideal candidate for a lateral versus a traditional approach, and versus a hybrid construct. The objective of this study is to present a method for utilizing the lateral minimally invasive surgery (MIS) approach for adult spinal deformity, provide clinical outcomes to validate our experience, and determine the limitations of lateral MIS for adult degenerative scoliosis correction.

Methods. Radiographic and clinical data were collected for patients who underwent surgical correction of adult degenerative scoliosis between 2007 and 2012. Patients were retrospectively classified by degree of deformity based on coronal Cobb angle, central sacral vertical line (CSVL), pelvic incidence, lumbar lordosis (LL), sagittal vertical axis (SVA), pelvic tilt (PT), presence of comorbidities, bone quality, and curve flexibility. Patients were placed into 1 of 3 groups according to the severity of deformity: “green” (mild), “yellow” (moderate), and “red” (severe). Clinical outcomes were determined by a visual analog scale (VAS) and the Oswestry Disability Index (ODI).

Results. Of 256 patients with adult degenerative scoliosis, 174 underwent a variant of the lateral approach. Of these 174 patients, 27 fit the strict inclusion/exclusion criteria ($n = 9$ in each of the 3 groups). Surgery in 17 patients was dictated by their category, and 10 were treated with surgery outside of their classification. The average age was 61 years old and the mean follow-up duration was 17 months. The green and yellow groups experienced a reduction in coronal Cobb angle (12° and 11° , respectively), and slight changes in CSVL, SVA, and PT, and LL. In the green group, the VAS and ODI improved by 35 and 17 points, respectively, while in the yellow group they improved by 36 and 33 points, respectively. The red subgroup showed a 22° decrease in coronal Cobb angle, 15° increase in LL, and slight changes in PT and SVA. Three patients placed in the yellow subgroup had “green” surgery, and experienced a coronal Cobb angle and LL decrease by 17° and 10° , respectively, and an SVA and PT increase by 1.3 cm and 5° , respectively. Seven patients placed in the red group who underwent “yellow” or “green” surgery had a reduction in coronal Cobb angle of 16° , CSVL of 0.1 cm, SVA of 2.8 cm, PT of 4° , VAS of 28 points, and ODI of 12 points; lumbar lordosis increased by 15° . Perioperative complications included 1 wound infection, transient postoperative thigh numbness in 2 cases, and transient groin pain in 1 patient.

Conclusions. Careful patient selection is important for the application of lateral minimally invasive techniques for adult degenerative scoliosis. Isolated lateral interbody fusion with or without instrumentation is suitable for patients with preserved spinopelvic harmony. Moderate sagittal deformity (compensated with pelvic retroversion) may be addressed with advanced derivatives of the lateral approach, such as releasing the anterior longitudinal ligament. For patients with severe deformity, the lateral approach may be used for anterior column support and to augment arthrodesis.

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KEY WORDS • adult spinal deformity • adult degenerative scoliosis •
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direct lateral interbody fusion • minimally invasive surgery • complications

MINIMALLY invasive spine surgery was developed to address approach-related morbidity associated with traditional open spine surgery. Over the last decade the application of MIS techniques for the

spine has continued to evolve and expand.^{4,5,9,12,16,22,37} As the field continues to advance, MIS techniques have been implemented in the treatment of more complex patient pathologies, including adult degenerative scoliosis, the prevalence of which has increased due to increasing life expectancy. In recent publications, Wang et al. described techniques for mini-open pedicle subtraction osteotomy as well as percutaneous iliac screw placement, which may become invaluable tools in the future treatment of adult degenerative scoliosis.^{37–39} The traditional surgical cor-

Abbreviations used in this paper: ALIF = anterior lumbar interbody fusion; ALL = anterior longitudinal ligament; CSVL = central sacral vertical line; LL = lumbar lordosis; MIS = minimally invasive surgery; ODI = Oswestry Disability Index; PI = pelvic incidence; PT = pelvic tilt; SVA = sagittal vertical axis; VAS = visual analog scale.

rection of adult degenerative scoliosis incorporates extensive open spinal mobilization and then reconstruction with long multilevel implants, and may confer significant morbidity. Less invasive techniques have the potential for muscle mass preservation and decreased physiological stress, blood loss, narcotic use, and length of hospital stay. However, MIS techniques have their own set of challenges and complications. Difficulties related to MIS correction of adult degenerative scoliosis are particularly associated with its steep learning curve and technical limitations, and require a full understanding of the fundamentals of spinal deformity correction as well as the technical limitations of MIS instrumentation.

Lateral MIS instrumentation techniques have played an increasing role in the treatment of adult degenerative scoliosis, which is characterized by spinal curvature greater than 10° with associated derangement of spinopelvic alignment.^{1,6,28} It can be used as a unique stand-alone treatment, or as a source of anterior column support to provide fusion and possible deformity correction. Progressive deformity that develops after skeletal maturity is related to asymmetrical degeneration of intervertebral discs, compression fractures, and/or osteoporosis. Classification of adult degenerative scoliosis severity, both radiographically and clinically, is critical to selecting the appropriate treatment paradigm.³⁰ The timing of surgical intervention, the surgical approach, and the length of constructs for operative correction have been controversial.

Patient selection is an important factor when electing to use an MIS approach, because not all patients are candidates for this approach due to the extent of deformity. The MIS decision-making process includes a thorough analysis of clinical and radiographic parameters to establish benchmark surgical objectives for neural decompression, restoration, and maintenance of spinal balance in a similar fashion to traditional open techniques. Each lateral MIS surgical technique or variation has its unique impact on deformity correction and can be used alone or combined with others. There is a paucity of data in determining the ideal candidate for a lateral MIS versus a traditional open approach, and versus hybrid constructs. In this paper we present a follow-up study of our single-center experience with the lateral MIS technique for adult degenerative scoliosis, with a refined understanding of the importance of sagittal balance correction.⁹

The purpose of this project is to provide a roadmap to guide the surgical treatment of adult degenerative scoliosis using minimally invasive lateral anterior/posterior interbody arthrodesis, anterior column release, posterior decompression, and posterior percutaneous instrumentation. We also discuss the use of hybrid constructs incorporating traditional posterior osteotomies. Our objectives of this project are to: 1) present and validate a surgical method for utilization of the lateral MIS approach for adult degenerative scoliosis; 2) analyze construct-specific clinical outcomes and complications; and 3) determine the limitation of lateral MIS for adult degenerative scoliosis. We discuss specific strategies we have developed and refined for realizing these objectives using our institutional standardized MIS adult degenerative scoliosis classification.

Methods

Data Collection

In an effort to deliver reproducible outcomes, we performed a retrospective review of a prospectively acquired database of patients who underwent lateral MIS correction of adult degenerative scoliosis at the University of South Florida between 2007 and 2012. Initial clinical evaluation was performed by the senior author (J.S.U.) and included a detailed history and physical examination to determine signs and symptoms, comorbidities, bone quality, and age. Spinopelvic parameters as well as clinical outcomes were measured and recorded both preoperatively and postoperatively. Patients were classified by degree of deformity based on coronal Cobb angle, PI, LL, SVA, PT, presence of comorbidities, and curve flexibility. The presence of a fractional curve at L5/S1 was also evaluated for treatment options.

Outcome Measures and Follow-Up

Outcome measures included integrity of the construct, degree of correction, complications, fusion rates, and VAS and ODI patient questionnaires. Outcome questionnaires were obtained at each interval follow-up period. Clinical follow-up evaluation was scheduled postoperatively at 4 weeks, 3 months, 6 months, 1 year, and 2 years from the date of surgery. Inclusion criteria of the study were: 1) presence of spinal deformity (characterized by coronal Cobb angle $> 10^\circ$); 2) having undergone lateral MIS or hybrid approach for arthrodesis and correction; 3) minimum of 12-month clinical follow-up with outcome measures; 4) adequate preoperative and postoperative 36-inch standing radiographs; and 5) 12-month CT scan. Exclusion criteria were: 1) severe medical comorbidities that would render a patient unable to tolerate adult degenerative scoliosis correction; 2) bone density less than -2.0 on preoperative dual-energy x-ray absorptiometry; 3) adolescent idiopathic scoliosis; 4) concurrent presence of Parkinson disease; 5) retroperitoneal fibrosis; 6) vascular anomalies prohibiting lateral access; and 7) previous surgical procedures for adult degenerative scoliosis correction.

Surgical Techniques

Surgeries performed included both MIS and open techniques. Included in the MIS group were the lateral retroperitoneal transpsoas approach, presacral lumbar interbody fusion, mini-open ALIF, mini-open transforaminal lumbar interbody fusion, posterior percutaneous pedicle screw fixation, ALL release from the lateral position, and segmental thoracolumbar release facetectomies. Open techniques included laminectomy/foraminotomy, open pedicle screw fixation, Smith-Petersen/Ponte osteotomies, and pedicle subtraction osteotomies. Fusion was determined using postoperative CT at 12 months. Complications were analyzed and recorded. Clinical score averages were determined preoperatively and at the most recent follow-up evaluation. The paired t-test was used to compare means. Probability values were determined for each clinical outcome measure.

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Surgical Subgroups

After 5 years of experience and knowledge gained from mistakes made with the lateral approach, we propose a guide for surgical decision making using radiographic parameters (Fig. 1), with the understanding that much more is involved. Patients with adequate sagittal balance (SVA < 5 cm) and spinopelvic harmony (PI-LL < 20° and PT < 25°) were placed into the green group (mild spinopelvic disharmony) and were considered suitable for a simple stand-alone construct or limited fusion at the apex of the curve with lateral MIS interbody fusion with or without posterior instrumentation. Patients with moderate spinopelvic disharmony (SVA 5–9 cm, PI-LL 20°–30°, and/or PT 25°–30°) were classified into the yellow group, requiring MIS interbody fusion with posterior instrumentation and the addition of ALL release or MIS facetectomy to obtain adequate correction. Finally, patients with severe spinopelvic malalignment (SVA > 10 cm with fixed curves, PT > 30°, and/or PI-LL > 30°) were classified into the red group and likely to require traditional open posterior osteotomies with or without multilevel ALL release hybrid constructs to obtain adequate correction. At our institution, not all patients fall into these surgical categories, which will be discussed in the following section.

Results

Of 256 patients with adult degenerative scoliosis, defined as having a coronal Cobb angle greater than 10°, 174 underwent surgical intervention using a variant of the lateral approach. Of those 174 patients, 27 fit the inclusion/exclusion criteria. Among these 27 patients, there were 11 males and 16 females, with an average age of 61 years and a mean follow-up duration of 17 months.

There were 9 patients in each group, but 10 patients (3 in the yellow group and 7 in the red group) underwent a less extensive surgery than we discuss in our categorization scheme (“undertreated” classification). There were

no statistically significant differences in the ages or follow-up durations between the groups (Tables 1 and 2). All patients achieved adequate fusion, as determined using a 12-month postoperative CT scan read by a radiologist as well as a member of the surgical team. Perioperative complications included 1 patient with a deep wound infection requiring debridement and intravenous antibiotics (4%), 2 patients (8%) with transient postoperative anterior thigh numbness ipsilateral to the side of approach in the distribution of the lateral femoral cutaneous nerve (Zone 2), and 1 patient (4%) with transient groin pain in the distribution of the ilioinguinal nerve (Zone 1).² Tables 3 and 4 list changes in parameters for each subgroup from preoperatively to postoperatively.

Green Group

The green subgroup included 9 patients classified into the “green” category that underwent a “green” surgery. No patients in this subgroup received the incorrect surgery according to the classification scheme. The coronal Cobb angle decreased by 12° (p < 0.001), CSVL increased by 0.2 cm (p = 0.717), SVA increased by 0.6 cm (p = 0.9), PT increased by 1° (p = 0.52), and LL increased by 1° (p = 0.67). The VAS and ODI scores decreased by 35 (p = 0.004) and 17 (p = 0.006) points, respectively.

Yellow Group

The yellow subgroup included 6 patients classified into the “yellow” category who underwent a “yellow” surgery. Coronal Cobb angle had a statistically significant decrease of 11° (p = 0.001), CSVL decreased by 0.7 cm, SVA decreased by 1.4 cm, PT decreased by 1°, and LL increased by 7° (p = 0.02). The VAS and ODI scores both demonstrated statistically significant decreases of 36 (p = 0.03) and 33 (p = 0.002), respectively.

Yellow Undertreated Group

The yellow undertreated subgroup contained the 3 patients classified into the “yellow” category who un-

	Mild	Moderate	Severe
CCA	<30°	>30	>30
PI-LL	<20°	20° - 30°	>30°
SVA	<5cm	5 - 9cm	>10cm
PT	<25°	25-30°	>30°
Anterior arthrodesis	Limited MIS-LIF consider standalone if PT<20°	MIS-LIF to neutral vertebrae + ALLR	MIS-LIF to neutral vertebrae ± ALLR
Posterior fixation	Percutaneous fixation	Percutaneous fixation ± facetectomy	Pedicle screw fixation + osteotomy

Fig. 1. Radiographic subgroups and related surgical intervention. **Green:** Represents radiographic parameters of patients with mild symptomatic deformity and spinopelvic compensation. **Yellow:** Represents radiographic parameters of patients with moderate symptomatic deformity and associated lack of sagittal balance with SVA between 5 cm and 9 cm. **Red:** Represents radiographic parameters of patients with severe symptomatic deformity and associated lack of sagittal balance with SVA greater than 10 cm despite maximal PT. ALLR = ALL release; CCA = coronal Cobb angle; LIF = lateral interbody fusion.

TABLE 1: Cohort demographics

Group	No. of Patients (M/F)	Age Range (average)*	Average Follow-Up (mos)
green	9 (4/5)	61–71 (67)	15.2
yellow	6 (3/3)	53–66 (59)	18
yellow undertreated	3 (0/3)	54–74 (62)	16
red	2 (0/2)	59–69 (65)	19
red undertreated	7 (4/3)	32–73 (53)	18

* Age given in years.

derwent a “green” surgery, and showed no statistically significant different values preoperatively to postoperatively. Coronal Cobb angle, LL, VAS, and ODI decreased by 17°, 10°, 30 points, and 17 points, respectively. The CSVL, SVA, and PT increased by 0.3 cm, 1.3 cm, and 5°, respectively.

Red Group

The red subgroup contained the 2 patients classified into the “red” category who underwent a “red” surgery. The coronal Cobb angle, SVA, PT, VAS, and ODI decreased by 22°, 0.1 cm, 1°, 15 points, and 10 points, respectively, while the CSVL and LL increased by 1.5 cm ($p = 0.009$) and 15°, respectively.

Red Undertreated Group

The red undertreated subgroup contained 7 patients classified into the “red” category who underwent either a “yellow” or a “green” surgery. The coronal Cobb angle, CSVL, SVA, PT, VAS, and ODI decreased by 16° ($p = 0.003$), 0.1 cm, 2.8 cm, 4°, 28 points, and 12 points, respectively, while the LL increased by 15° ($p = 0.04$).

Illustrative Cases

Case 7 (Green Group)

This patient was a 67-year-old retired man referred for 20 years of progressively worsening low-back pain, characterized as bandlike across the musculature of the lower back, radiating occasionally to the left gluteal region. He was neurologically intact and underwent unsuccessful nonoperative therapy. Radiographic imaging at initial presentation demonstrated dextroscoliosis with a coronal Cobb angle of 16°. His CSVL, SVA, PT, PI, and LL measured 1 cm, 2 cm, 24°, 74°, and 60°, respectively, which placed him in the “green” group. Additional radiographic findings included extensive degenerative disease, disc bulges, and central canal and foraminal stenosis at multiple levels. Preoperative VAS and ODI scores were 67 and 28, respectively. He was subsequently treated with L1–5 extreme lateral interbody fusion (Nuvasive, Inc.), and L1–5 percutaneous pedicle screws (“green” surgery). The patient had an uneventful postoperative course. At the most recent follow-up evaluation the patient’s coronal Cobb angle, CSVL, SVA, PT, PI, and LL measured 10°, 1 cm, 0 cm, 25°, 74°, and 61°, respectively, while the VAS and ODI scores were 0 and 11.1 points, respectively (Fig. 2).

Case 12 (Yellow Group)

This patient was a 58-year-old retired woman with a long history of low-back pain, bilateral gluteal pain, and paresthesias radiating to the lower extremities. The patient did not experience loss of bowel or bladder control, and nonoperative therapies were unsuccessful. Preoperative imaging demonstrated dextroscoliosis with a coronal Cobb angle of 23°, and CSVL, SVA, PT, PI, and LL measurements of 2 cm, 8 cm, 15°, 67°, and 51°, respectively, which placed her in the “yellow” group. Her preoperative VAS and ODI scores were 100 and 84, respectively. She was subsequently treated with L2–5 lateral interbody fusions, L2–3 and L3–4 ALL release, L5–S1 ALIF, with L2–iliac instrumentation (“yellow” surgery). Her postoperative course was complicated by a surgical site infection that was secondarily reopened and debrided, treated with antibiotics, and subsequently healed well. She experienced marked symptom resolution, with a postoperative coronal Cobb angle of 14°, and CSVL, SVA, PT, PI, and LL measurements of 1 cm, 0 cm, 14°, 67°, and 56°, respectively. Her postoperative VAS and ODI scores were 60 and 42, respectively (Fig. 3).

Case 24 (Red Undertreated Group)

This patient was a 67-year-old man with chronic back pain with intermittent radiating symptoms in his right leg. Walking and standing aggravated the symptoms. He had tried nonoperative therapies without success. He denied any weakness or urinary incontinence. Preoperative parameters were a coronal Cobb angle of 54°, CSVL 2 cm, SVA 12 cm, PT 40°, PI 71°, and LL 35°, which placed him in the “red” group. His dual x-ray absorptiometry scan was within normal limits. He subsequently underwent lateral interbody fusions from T-12 to L-5 and an ALIF at L5–S1. He had 2 levels of ALL release at L2–3 and L3–4. This was followed by Stage II surgery, including posterior percutaneous pedicle screw fixation from T-10 to the sacrum (“yellow” surgery). Postoperative imaging demonstrated a coronal Cobb angle of 29°, CSVL 6 cm, SVA 5 cm, PT 26°, PI 71°, and LL 74°. His postoperative course was uneventful, and at the most recent follow-up evaluation his VAS score had improved from 76 to 53 and his ODI score had improved from 50 to 30 (Fig. 4).

Discussion

Adult degenerative scoliosis encompasses a wide spectrum of spinal deformity associated with a loss of

TABLE 2: Characteristics of patients classified by varying degrees of spinal deformity*

Case No.	Group	Age (yrs), Sex	Interbody Fusion Levels	ALL Release Levels	Posterior Fixation	Fusion	Follow-Up (mos)	Complications
1	green	70, M	L2-4	none	PPS, L2-4	yes	12	
2	green	68, F	L4-5	none	PPS, L4-5	yes	12	
3	green	61, M	L4-5	none	PPS, L4-5	yes	12	transient rt anterior thigh numbness consistent w/ Zone 3
4	green	74, F	L2-4, L4-5 (stand-alone)	none	none	yes	12	
5	green	63, F	L2-5	none	PPS, L2-5	yes	12	
6	green	71, M	L3-4 (stand-alone)	none	none	yes	12	
7	green	67, M	L1-5	none	PPS, L1-5	yes	12	
8	green	64, F	L2-S1	none	PPS, L2-S1	yes	12	
9	green	62, F	L1-S1	none	PPS, T12-S1	yes	41	
10	yellow	60, F	L2-5	L2-4	PPS, L2-iliac	yes	24	transient groin pain corresponding to Zone 2
11	yellow	74, M	L2-S1	L3-4	OPS, L1-iliac	yes	24	
12	yellow	58, F	L2-S1	L2-4	PPS, L2-iliac	yes	12	wound infection
13	yellow	60, M	L1-S1	L3-4	PPS, T11-S1	yes	12	
14	yellow	64, F	L2-S1	L3-4	PPS, L2-S1	yes	12	
15	yellow	54, M	L1-5	L3-4	PPS, L1-5	yes	12	
16	yellow undertreated	53, F	T12-S1	none	PPS, T12-S1	yes	12	
17	yellow undertreated	57, F	L2-S1	none	PPS, L2-S1	yes	30	
18	yellow undertreated	66, F	L2-S1	none	PPS, L2-S1	yes	12	
19	red	32, F	L1-S1 (L1-2 SPO)	none	OPS, T9-iliac	yes	24	transient rt anterior thigh numbness consistent w/ Zone 3
20	red	73, F	L1-5 (L1-2 SPO)	L1-2	OPS, T10-iliac	yes	12	
21	red undertreated	62, F	L4-5	none	PPS, L4-5	yes	12	
22	red undertreated	59, M	L2-5	none	PPS, L2-5	yes	24	
23	red undertreated	69, F	T12-S1	none	PPS, T10-S1	yes	12	
24	red undertreated	67, M	T12-S1	T12-L1, L2-4	PPS, T10-S1	yes	42	
25	red undertreated	64, M	L1-5	L2-4	OPS, T12-L5	yes	24	
26	red undertreated	64, M	L2-5	L2-4	PPS, L2-5	yes	12	
27	red undertreated	69, F	L2-5	none	PPS, L2-5	yes	12	

* ALLR = anterior longitudinal ligament release; OPS = open pedicle screws; PPS = percutaneous pedicle screws; SPO = Smith-Petersen osteotomy.

TABLE 3: Change in average preoperatively and postoperatively measured spinopelvic parameters*

Group	Δ CCA (°)	p Value	Δ CSVL (cm)	p Value	Δ SVA (cm)	p Value	Δ PT (°)	p Value	Δ LL (°)	p Value	Δ VAS	p Value	Δ ODI	p Value
green	-12	<0.001	0.2	0.717	0.6	0.9	1	0.52	1	0.665	-35	0.004	-17	0.006
yellow	-11	0.001	-0.7	0.58	-1.4	0.52	-1	0.4	7	0.02	-36	0.03	-33	0.002
yellow undertreated	-17	0.19	0.3	0.29	1.3	0.6	5	0.26	-10	0.18	-30	0.26	-17	0.2
red	-22	0.48	1.5	0.009	-0.1	0.94	-1	0.76	15	0.32	-15	0.21	-10	0.65
red undertreated	-16	0.003	-0.1	0.94	-2.8	0.26	-4	0.24	15	0.04	-28	0.21	-12	0.65

* Statistically significant values shown in bold. CCA = coronal Cobb angle.

sagittal, coronal, and axial balance.^{21,28} Studies of patients with spinal deformity by Schwab et al. have demonstrated that global spinal malalignment is a strong predictor of disability and that failure to account for pelvic alignment when treating spinal deformity increases the risk for global imbalance, decompensation, and treatment failure.^{24–27} Studies show that health-related quality of life scores following surgery for adult degenerative scoliosis are strongly correlated with the achievement of sagittal balance (SVA < 5 cm) and spinopelvic harmony (PT < 25°, PI-LL mismatch < 9°).^{3,24–27}

The surgeon who corrects the deformity must be prepared to offer both minimally invasive as well as traditional open surgical correction in this diverse patient population. Numerous studies have shown that MIS techniques decrease costs, preserve postoperative muscle mass, decrease physiological stress on the patient, and improve perioperative complications such as blood loss, infection, and narcotic use.^{13,19,23,31,36} Specifically, percutaneous pedicle screws, anterolateral approaches, neuromonitoring, specialized instrumentation for deformity correction, improved imaging, and bone morphogenetic protein have been critical in allowing spine surgeons to manage these complex pathologies in a minimally invasive fashion.^{4,5,9,11,12,14,22,34,35,38} However, with MIS treatment of spinal deformity, the ability to provide correction is limited with respect to what traditional open techniques can provide.

With the problems that arise with revision surgery for deformity, including a more challenging procedure and higher complication rates, the importance of performing the correct procedure initially is magnified.^{7,8,15,17,18,20,29} The surgeons capable of performing open and MIS techniques for deformity should then ask themselves: “What is the least amount of surgery for this particular patient that will improve symptoms, improve sagittal balance, and achieve spinopelvic harmony?”⁴ For the lateral access surgeon, the question may be: “In which patient population will a stand-alone lateral interbody fusion at the coronal apex suffice? Or will this patient need more sagittal correction, requiring an ALL release and lateral interbody cage placement, providing anterior column support and delivering graft for fusion, combined with posterior osteotomies.” Although there is a growing literature base concerning the lateral treatment of adult spinal deformity, there remains a paucity of data on when and how it should be implemented.^{4,5,9,11,12} The authors seek a radiographic roadmap with respect to the lateral approach for treating spinal deformity.

In addition to obtaining a thorough history and performing a physical examination, the key factors used in our study to separate patients into categories were coronal Cobb angle, PI-LL mismatch, SVA, PT, comorbidities, and curve flexibility. Patients were assigned to a color category based on the worst radiographic skeletal criteria. For example, if a patient’s SVA was < 5 cm but the PI-LL mismatch was 20°–30°, they were classified into the yellow, or worse, group. This system explains certain anomalies in our data, such as the average PT in the yellow group that was 18° preoperatively.

Patients with a mild coronal imbalance (coronal Cobb

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TABLE 4: Comparison of average preoperatively and postoperatively measured spinopelvic parameters

Group	CCA (°)	CSVL (cm)	SVA (cm)	PT (°)	PI (°)	LL (°)	VAS	ODI
green								
preop	23	2	2	18	58	55	74	47
postop	11	2	2	19	58	56	39	30
yellow								
preop	22	2	5	18	56	37	89	64
postop	11	1	4	17	58	44	53	31
yellow undertreated								
preop	32	1	0	26	72	55	82	63
postop	15	2	1	31	71	45	52	46
red								
preop	44	1	6	36	71	32	85	70
postop	22	2	6	35	72	47	70	60
red undertreated								
preop	29	4	7	32	68	39	60	44
postop	13	4	4	29	68	54	41	32

angle < 30°), who are sagittally neutral (SVA < 5 cm), with a flexible curve, comorbidities, a PT < 20°, and a minimal PI-LL mismatch of < 20° may be candidates for stand-alone lateral interbody fusion (green group). This is a good option for those fragile patients without other surgical options, limited by age (> 80 years old) or multiple severe comorbidities. The impact on sagittal balance is minimal, but surgery may limit curve progression as well as provide indirect decompression at the same time. Also in the green group are the patients who are similar

except for a PT of 20°–25° but who remain sagittally neutral (SVA < 5 cm) and without significant comorbidities. For that patient, the role of the lateral approach may be for multiple interbody fusions limited to the apex of a small coronal curve. Taken together, the patients in the green group had a coronal Cobb angle improvement of 12°, from 23° to 11°, which was statistically significant ($p < 0.001$). As could be expected in this group with minimal deformity, the changes in SVA, PT, and LL were small and not statistically significant. However, there was a



Fig. 2. Case 7. Anteroposterior and lateral 36-inch radiographs of a patient with mild deformity (green group). **A:** Preoperative images of a patient with mild compensated deformity. **B:** Postoperative images obtained after L1–5 MIS-lateral interbody fusion and percutaneous posterior fixation showing restoration of disc height, improvement in coronal Cobb angle, and no significant change in other spinopelvic parameters.



FIG. 3. Case 12. Anteroposterior and lateral 36-inch radiographs of a patient with moderate deformity (yellow group). **A:** Preoperative images of a patient with moderate deformity. **B:** Postoperative images obtained after L2–5 MIS-lateral interbody fusion with ALL release and posterior fixation from L-2 to the ilium, showing restoration of disc height and improvement in spinopelvic parameters.

statistically significant reduction in the VAS of 35 points ($p = 0.004$), while the ODI approached statistical significance with a 17-point reduction ($p = 0.006$). Interestingly, in the green group the SVA increased by an average of 0.6 cm ($p = 0.717$), likely resulting from not attempting to increase sagittal balance in this patient population; however, this increase apparently had minimal impact on clinical outcomes. Making efforts to increase the lumbar

lordosis and overcorrecting sagittal balance in these patients would likely have required a larger surgery, may not necessarily have improved outcome measures, and increased the risk of complications (Tables 3 and 4).

The yellow group included 9 patients with moderate adult degenerative scoliosis, with a coronal Cobb angle $> 30^\circ$, a PI-LL mismatch of 20° – 30° , with compensated (PT 25° – 30°) positive sagittal balance (SVA 5–9 cm), a

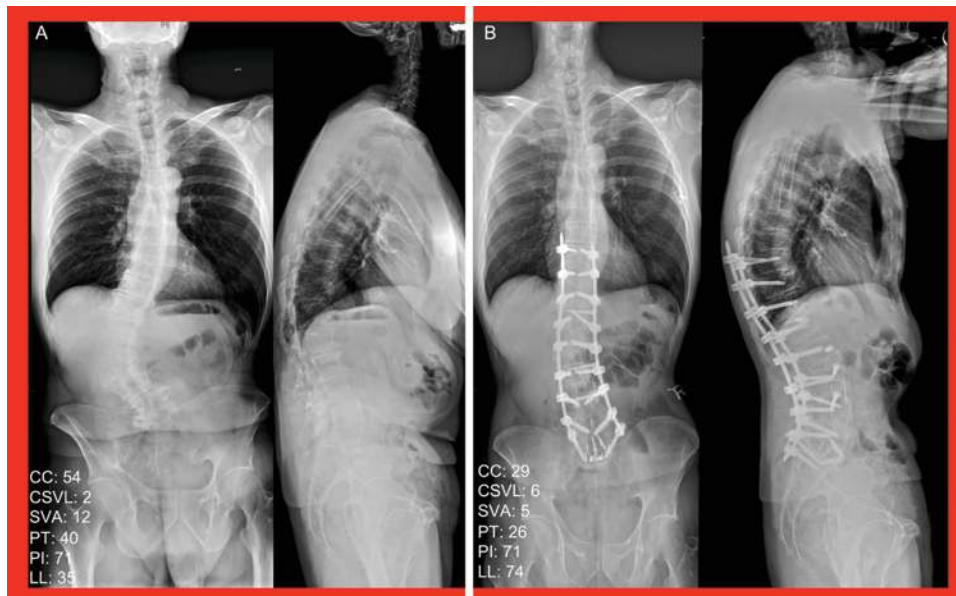


FIG. 4. Case 24. Anteroposterior and lateral 36-inch radiographs of a patient with severe deformity (red group). **A:** Preoperative images of a patient with severe deformity. **B:** Postoperative images obtained after T10–S1 open posterior arthrodesis with osteotomies and with MIS-lateral interbody fusion with multilevel ALL release, showing restoration of disc height and improvement in spinopelvic parameters.

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flexible curve, and no significant medical comorbidities. Six of the 9 patients classified into this subgroup underwent surgery consistent with our roadmap. Statistically significant measurements in this group were a coronal Cobb angle decrease of 11°, from 22° to 11° ($p < 0.001$), LL increase from 37° to 44° ($p = 0.02$), and improvements in VAS and ODI scores of 36 ($p = 0.03$) and 33 ($p = 0.002$) points, respectively. The average changes in CSVL, SVA, and PT were small and not statistically significant. On average, the PI-LL mismatch decreased from 29° to 14° for this group. Overall, the most significant aspect of the yellow group was not a change in radiographic parameter, but rather the statistically significant improvement in patient outcome scores.

Three of the 9 patients in the “yellow” category had less extensive surgery (“green”) than suggested in our roadmap (the yellow undertreated group). No parameters in this subgroup had values of statistical significance, likely resulting from the small number of patients. Although the coronal Cobb angle decreased by 17°, the SVA, PT, and LL all increased, worsening spinopelvic parameters. This worsening was likely due to surgical undercorrection, and was understood by our surgical team as a learning point.

The red group was composed of 9 patients, and included those with severe sagittal imbalance whose compensatory mechanisms were maximized ($PT > 30^\circ$, $PI-LL > 30^\circ$, and thoracic hypokyphosis, although not included in this study). The surgery we recommend for these sagittally decompensated patients, although in the past have not always provided, includes the previously discussed lateral MIS techniques with either Ponte osteotomies if the SVA is less than 14 cm, or a pedicle subtraction osteotomy if the SVA is greater than 14 cm. To maximize sagittal improvement in these patients, an L5–S1 ALIF should almost always be performed. Two of the 9 patients classified into this subgroup underwent surgery consistent with our roadmap; however, due to the small number of patients in this cohort, all measurements were statistically insignificant, except for the change in CSVL, which increased by 1.5 cm ($p = 0.009$). Although the VAS and ODI scores improved by 15 and 10 points, respectively, they were not statistically significant. Despite the small cohort, treating the “red” group with “red” surgery improved most radiographic values, including coronal Cobb angle (decreased by 22°), PT (decreased by 1°), and LL (increased by 15°).

Seven of the 9 patients in the “red” category received less surgery (“green” or “yellow”) than suggested in our roadmap (red undertreated group). Statistically significant values in this group included a decrease in coronal Cobb angle of 16° ($p = 0.003$), and an increase in LL of 15° ($p = 0.04$). All other values improved, including CSVL (decrease by 0.1 cm), SVA (decrease by 2.8 cm), PT (decrease by 4°), and VAS and ODI scores (decrease by 28 and 12 points, respectively).

The prior 5 years of incorporating the lateral approach to our surgical armamentarium have been a learning experience. As demonstrated in the current study, many of our patients with positive sagittal alignment have been undercorrected using the lateral approach. Future innovations will likely allow significant improvement in

sagittal balance and thus improvements in clinical outcome and reduction in reoperation rates.

This study should not be taken as an algorithm on how to treat adult degenerative scoliosis from a minimally invasive approach. Rather, it is a description of our experience and lessons learned in treating a difficult group of patients, especially with our previous report of inadequate sagittal correction in one-third of a cohort undergoing lateral MIS for adult degenerative scoliosis.⁹ Through preoperative and postoperative radiographic measures and patient-reported outcomes analysis, the authors discuss a suitable approach to help guide surgical treatment, including decompression, instrumented posterior spinal fusion, anterior spinal fusion, and osteotomy, with a focus on the lateral approach. The clinical gains of minimally invasive techniques, when applied to these cases, may be even greater by diminishing exposure-related morbidity. While the surgical literature remains limited to preliminary experiences and early short-term results, our experience and an expansion of our knowledge with these advanced techniques is progressing swiftly.

Future Challenges

A major challenge with lateral MIS techniques is that they are powerful when correcting coronal imbalance, but when used without additional anterior or posterior releases they will likely have a minimal impact on lumbar lordosis and subsequently on sagittal balance, as demonstrated in our study. The potential for a poor outcome if basic spinopelvic parameters are not maintained has been discussed, and should be in the thoughts of any surgeon performing lateral MIS for adult degenerative scoliosis.

For these techniques to become the standard of care, a number of impediments to individual adoption must be acknowledged and overcome. First, one of the primary barriers to the application of this technology is related to the steep learning curve associated with these techniques. Second, MIS techniques require a strong understanding of 3D spinal anatomy. At our institution, surgeons undergo multiple anatomical, biomechanical, and cadaveric training sessions to refine skills and avoid the complications of these techniques.^{10,12,33} Finally, unforeseen health care changes have the potential to diminish funding for new product development. Modern instrumentation has been developed for longer-segment fixation, fusion, and segmental manipulation, making MIS for deformities a feasible option in select patients. We learned after 5 years of using the lateral approach that it is versatile and may play a significant role in adult degenerative scoliosis when used correctly and for the correct indication.

Study Limitations

In addition to the complexity of spinopelvic parameters, the growing number of surgical procedures, both in the minimally invasive and traditional realms, makes any classification scheme from a lateral MIS perspective difficult. However, we believe that some basic principles, as outlined in this study, may be used as a roadmap when approaching adult degenerative scoliosis from a lateral approach.

Radiographic outcomes in this series are likely to be inferior in terms of deformity correction when compared with an open surgical series. As an evolving discipline, minimally invasive deformity surgery currently lags behind traditional techniques such as open osteotomy, mainly due to technological limitations. While this is currently an area of active research, it remains a trade-off when trying to achieve lower complication rates than those associated with open surgery. In addition, the lack of dorsal bone exposure for a fusion surface will likely result in higher rates of pseudarthrosis at segments where an interbody fusion is not performed.

The emerging importance of 36-inch standing radiographs has altered the treatment paradigms of spine surgery. At our institution, only in the last 24 months have these radiographs been consistently maintained on all patients. In addition, although attempts are made to have every patient return outcome measures to us, we are not always successful, which causes a limitation in the available number of patients for the current study. However, the relatively few publications on this topic have inadequate outcome measurements and are lacking in 36-inch standing radiographs. For this reason, our cohort (n = 27) is one of the largest in the literature with regards to lateral MIS for adult degenerative scoliosis correction.^{4,9,32}

Conclusions

The potential of the lateral approach in the treatment of adult degenerative scoliosis has yet to be realized. It is a versatile option for almost all types of adult deformity surgery, and will continue to evolve in this rapidly changing field of MIS. This study is an early attempt to determine when and how it can be used. For the patient with uncompensated and minimal sagittal and coronal imbalance (green subgroup), our outcomes show that a stand-alone or limited segmental lateral interbody fusion with posterior fixation at the curve apex should be adequate. For the yellow subgroup (moderate deformity), correction of sagittal imbalance can be achieved through some combination of lateral ALL release with or without MIS facetectomy with posterior fixation. For more severe deformity (red subgroup, sagittally unbalanced with rigid deformity curves), a hybrid MIS–open procedure will likely be needed. However, the lateral approach may be used in these cases for either an ALL release with hyperlordotic cage placement or interbody fusions for anterior column support and arthrodesis.

Disclosure

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