Transfacet Minimally Invasive Transforaminal Lumbar Interbody Fusion With an Expandable Interbody Device—Part II: Consecutive Case Series

Jawad M. Khalifeh, BS
Christopher F. Dibble, MD, PhD
Priscilla Stecher, BS
Ian Dorward, MD
Ammar H. Hawasli, MD, PhD
Wilson Z. Ray, MD

Department of Neurological Surgery, Washington University School of Medicine, St. Louis, Missouri

Correspondence:
Wilson Z. Ray, MD,
Department of Neurological Surgery,
Washington University School of Medicine,
660 S Euclid Ave, Campus Box 8057,
St. Louis, MO 63110, USA.
Email: rayz@wustl.edu

Received, November 19, 2019.
Accepted, March 21, 2020.

BACKGROUND: Advances in operative techniques and instrumentation technology have evolved to maximize patient outcomes following minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF). The *transfacet* MIS-TLIF is a modified approach to the standard MIS-TLIF that leverages a bony working corridor to access the disc space for discectomy and interbody device placement.
OBJECTIVE: To evaluate clinical and radiographic results following *transfacet* MIS-TLIF using an expandable interbody device.
METHODS: We performed a retrospective review of consecutive patients who underwent *transfacet* MIS-TLIF for degenerative lumbar spondylolisthesis. Patient-reported outcome measures for pain and disability were assessed. Sagittal lumbar segmental parameters and regional lumbopelvic parameters were assessed on upright lateral radiographs obtained preoperatively and during follow-up.
RESULTS: A total of 68 patients (61.8% male) underwent *transfacet* MIS-TLIF at 74 levels. The mean age was 63.4 yr and the mean follow-up 15.2 mo. Patients experienced significant short- and long-term postoperative improvements on the numeric rating scale for low back pain (–2.3/10) and Oswestry Disability Index (−12.0/50). *Transfacet* MIS-TLIF was associated with an immediate and sustained reduction of spondylolisthesis, and an increase in index-level disc height (+0.71 cm), foraminal height (+0.28 cm), and segmental lordosis (+6.83°). Patients with preoperative hypolordosis (<40°) experienced significant increases in segmental (+9.10°) and overall lumbar lordosis (+8.65°). Pelvic parameters were not significantly changed, regardless of preoperative alignment. Device subsidence was observed in 6/74 (8.1%) levels, and fusion in 50/53 (94.3%) levels after 12 mo.
CONCLUSION: *Transfacet* MIS-TLIF was associated with clinical improvements and restoration of radiographic sagittal segmental parameters. Regional alignment correction was observed among patients with hypolordosis at baseline.

KEY WORDS: Minimally invasive lumbar fusion, *Transfacet* MIS-TLIF, Indirect decompression, Expandable interbody device, Spondylolisthesis

Operative Neurosurgery 0:1–12, 2020 DOI: 10.1093/ons/opaa144

Minimally invasive spine surgery (MISS) has progressed significantly in the past 2 decades.[1] Advances in image guidance and instrumentation technology have evolved to maximize patient-reported outcomes (PROs) and radiographic results. Compared to traditional open approaches, MISS is associated with decreased operative blood loss, shorter lengths of stay, more rapid mobilization, lower opioid use, and earlier return to work,[1-5] while

ABBREVIATIONS: DH, disc height; **FH,** foraminal height; **MCID,** minimum clinically important difference; **MISS,** minimally invasive spine surgery; **MIS-TLIF,** minimally invasive transforaminal lumbar interbody fusion; **NRS,** numeric rating scale; **ODI,** Oswestry Disability Index; **OLL,** overall lumbar lordosis; **PEEK,** polyetheretherketone; **PI,** pelvic incidence; **PRO,** patient-reported outcome; **PT,** pelvic tilt; **SD,** standard deviation; **SL,** segmental lordosis; **SS,** sacral slope

Supplemental digital content is available for this article at www.operativeneurosurgery-online.com.

maintaining comparable long-term clinical outcomes and fusion rates.[6-8] The *transfacet* minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF), as described in a concurrently published report, is a proposed modification to the standard MIS-TLIF to treat lumbar degenerative diseases and low-grade spondylolisthesis.[2,9]

Transfacet MIS-TLIF with placement of an expandable interbody device achieves decompression of the affected nerve roots and spinal canal directly via discectomy and facetectomy and indirectly via disc height (DH) restoration and segmental realignment.[10,11] Expandable interbody devices can be placed with less risk to both exiting and traversing nerve roots and can be adjusted intraoperatively to restore DH and allow sufficient compression against the adjacent vertebrae to prevent migration.[12,13] Expandable interbody devices result in a large and sustained restoration of disc and neuroforaminal height, along with increased index-level segmental lordosis (SL), which may correlate with improved PROs.[11,14,15] Although regional lumbar and spinopelvic parameters are clinically meaningful outcomes in the context of deformity surgery,[16,17] their role in single-level MIS-TLIF for degenerative etiologies is unclear.[18-21] Studies that evaluated both clinical outcomes and regional lumbopelvic parameters after MIS-TLIF have not consistently demonstrated an association between the two.[11,14,22,23]

Although expandable interbody devices offer several advantages over static devices, there are concerns about late postoperative complications.[11,24] Patients treated with expandable interbody devices for various spinal pathologies may have an increased risk for vertebral endplate subsidence.[24-26] Reasons for subsidence are multifactorial, including bone quality or technical aspects related to endplate preparation, inappropriate device sizing or positioning, and overdistraction of the disc space with device expansion.[24,27] Implant properties, such as morphology and material, also contribute to subsidence risk.[8,27] Larger-diameter devices that cover greater surface areas are associated with less subsidence.[24,27,28] However, implanting a device with a large footplate is not always feasible, particularly with posterolateral MISS approaches. Lastly, titanium-based implants have a high modulus of elasticity relative to cortical and/or cancellous allograft bone, as compared with polyetheretherketone (PEEK) materials.[29] Modulus mismatches impart an increased risk for vertebral endplate violation, device subsidence, migration, and pseudarthroses.[29]

The objective of this study is to evaluate the clinical outcomes and radiographic results of *transfacet* MIS-TLIF with placement of an expandable interbody device. We report (1) PRO measures; (2) radiographic outcomes of sagittal segmental, regional lumbar, and pelvic parameters; and (3) interbody device subsidence and fusion rates.

METHODS

Patient Sample and Operative Intervention

This is a retrospective single-center case series of consecutive patients who underwent *transfacet* MIS-TLIF with an expandable interbody device at 1 or 2 adjacent levels. The operations were performed at an academic medical center between 2015 and 2018. The indications for surgery were lumbar degenerative disease with foraminal and/or central stenosis and segmental instability/grade I-II spondylolisthesis. The operative technique for *transfacet* MIS-TLIF is described in a concurrently published report.

The study was approved by our Institutional Review Board. Consent was waived, as this is a retrospective review of cases.

PRO Measures

We collected information on demographics, clinical characteristics, and operative details. PRO measures were assessed preoperatively and during routine postoperative clinic visits at 6 wk, 4 mo, 6 mo, 1 yr, and follow-up visits thereafter. We used the numeric rating scale (NRS/10) for pain intensity in the lower back and Oswestry Disability Index (ODI/50) for physical disability. The minimum clinically important difference (MCID) in patients undergoing lumbar spine surgery for the NRS back pain is estimated as 1.2 points and for the ODI as 12.8 points.[30]

Radiographic Outcome Measures

Sagittal segmental and lumbopelvic parameters were assessed on full-length upright lateral 36-inch radiographs of the lumbar spine with sufficient caudal coverage to accurately evaluate pelvic parameters. Serial radiographs were obtained preoperatively, postoperatively on day 1, and during routine postoperative follow-up at 6 wk, 4 mo, 6 mo, 1 yr, and additional visits thereafter.

Sagittal segmental parameters were DH, foraminal height (FH), SL, and amount of spondylolisthesis at the index level(s). DH was measured anteriorly, from inferior endplate of the rostral vertebra to the superior endplate of the caudal vertebra. FH was measured as the interpedicular distance.[31] SL (ie, fused segment angle) was measured as the lateral Cobb angle at the superior and inferior endplates of the fusion segment. The amount of listhesis was measured as the percentage offset (slip) of the vertebral body posterior wall relative to the adjacent caudal vertebral body.[32,33]

Sagittal lumbopelvic parameters were regional overall lumbar lordosis (OLL), pelvic incidence (PI), PI-OLL mismatch, sacral slope (SS) angle, and pelvic tilt (PT). OLL was measured as the lateral Cobb angle between the superior endplate of L1 vertebral body and the endplate of S1. PI, SS, and PT were measured as previously described.[34,35] PI-OLL mismatch was taken as the absolute difference between PI and OLL.

For patients with a minimum of 12 mo radiologic follow-up, interbody fusion was assessed on anterior and lateral radiographs, or CT scans when available, as solid bridging bone connecting the adjacent vertebral bodies across the interbody space or facet joints. Pseudarthrosis was defined as persistent motion at the "fused" segments on dynamic radiographs (greater than 5° of angular motion or 2 mm of translation), lucency around the screws, or instrumentation breakage/failure.[33,36] Device subsidence was assessed on all patients and defined as compromise of either caudal or rostral endplates on postoperative radiographs.

Statistical Analysis

Descriptive statistics were calculated for demographics, operative characteristics, and outcome measures. Continuous variables are presented using means and standard deviations (SD) and categorical variables using frequencies and percentages. Parametric tests for paired data were used to compare clinical and radiographic outcomes following *transfacet* MIS-TLIF. We made pairwise comparisons of each the 6-wk and 1-yr postoperative PRO measures relative to their baseline values.[37]

TABLE 1. Demographic and Operative Characteristics of Patients Who Underwent MIS-TLIF

Patient characteristics	All patients (N = 68 patients)
Number of MIS-TLIF levels	74 levels
Age at surgery, yr	63.4 (9.6) (range 29-82)
Preoperative BMI, kg/m^2	30.1 (5.2)
Sex	
Male	42 (61.8%)
Female	26 (38.2%)
Preoperative spondylolisthesis	
Grade I	61 (82.4%)
Grade II+	12 (16.2%)
Missing	1 (1.4%)
Operative levels	62 single level (83.8%)
L2/3	7 (9.5%)
L3/4	9 (12.2%)
L4/5	54 (73.0%)
L5/S1	4 (5.4%)
Side of complete facetectomy	
Left	58 (78.4%)
Right	15 (20.3%)
Bilateral	1 (1.4%)
Expandable cages	74 levels (100%)
Lordotic articulating	61 (82.4%)
Parallel	13 (17.6%)
Follow-up duration, mo	15.2 (8.8) (range 1.4-44.3)

BMI = body mass index.
Values are presented as n (%) for categorical variables or mean (SD) for continuous variables.

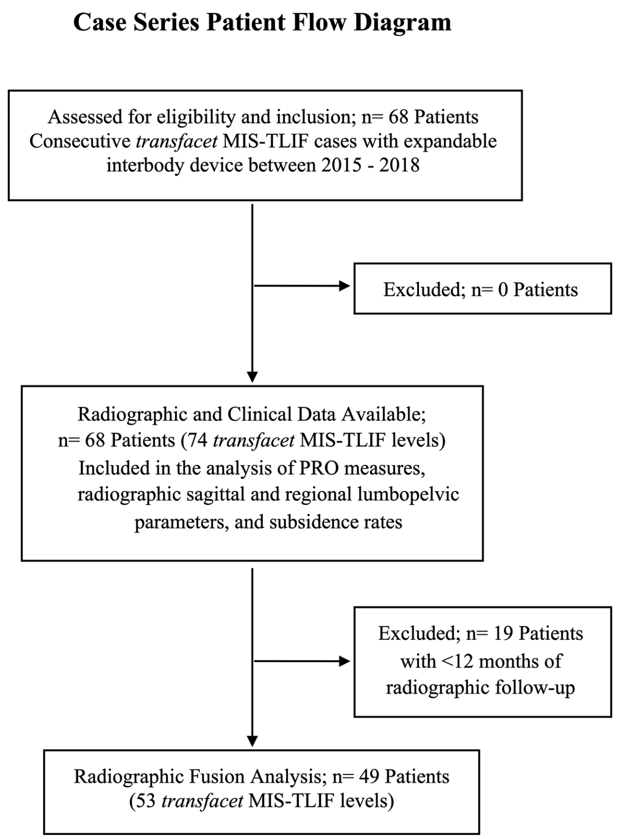


FIGURE 1. *Flow diagram providing details of patients included in the clinical study.*

For serial radiographic measurements data, we made pairwise comparisons of each "immediate" and "late" mean change in radiographic parameters relative to baseline.[37] The "immediate" time point refers to radiographs obtained on postoperative day 1, and "late" refers to radiographs obtained at the last available follow-up.

To evaluate the effects of *transfacet* MIS-TLIF on segmental (SL) and regional (OLL) spinal lordosis, we performed a stratified analysis of radiographic changes based on preoperative OLL: hypolordosis (<40°), normolordosis (40°-60°), and hyperlordosis (>60°) subgroups.[34] Additionally, we used linear regression to examine the relationship between the magnitude of change in SL and OLL against their corresponding preoperative values. This analysis was prespecified based on findings by Uribe et al[18] of segmental and regional lumbar alignment changes after MISS lumbar interbody fusion procedures, in which baseline sagittal parameters were found to affect the extent of correction gained.

A 2-sided P-value < .05 was considered statistically significant. Statistical analyses were performed using IBM SPSS Statistics v25 (IBM, Armonk, New York).

RESULTS

Baseline Characteristics: Demographics and Operative Details

A total of 68 patients (61.8% male) underwent *transfacet* MIS-TLIF at 74 levels (Table 1 and Figure 1). The mean age at surgery was 63.4 yr (SD 9.6, range 29-82). Most (54/74, 73.0%) procedures were performed at L4-L5. All (100%) patients received expandable interbody devices, of which 61/74 (82.4%) were the articulating type. The mean postoperative follow-up duration was 15.2 mo (SD 8.8, range 1.4-44.3), and 49/68 (72.1%) patients were included in the radiographic fusion analysis.

Patient-Reported Outcomes

Patients experienced significant improvements on self-reported measures of low back pain and disability following *transfacet* MIS-TLIF (Table 2 and Figure 2).

Mean NRS back pain decreased from 6.8/10 (SD 2.1) at baseline to 3.8 (SD 2.5) postoperatively at 6 wk, and 1.8 (SD 2.8) at 1 yr. Among patients with paired preoperative and either 6-wk or 1-yr postoperative NRS back pain, 12/19 (63.2%) and 13/16 (81.3%) achieved the MCID threshold of 1.2 points, respectively.

Similarly, the mean cumulative ODI score improved from 29.0/50 (SD 9.4) at baseline to 16.7 (SD 10.5) at 6 wk

TABLE 2. Patient-Reported Outcome (PRO) Measures

PRO measures, mean (SD)	Preoperative	6 wk postoperative	1 yr postoperative
NRS back pain score/10	6.8 (2.1), n = 62	3.8 (2.5), n = 20	1.8 (2.8), n = 18
Cumulative ODI score/50	29.0 (9.4), n = 60	16.7 (10.5), n = 62	10.0 (11.0), n = 43
Paired change in NRS back pain score (95% CI)		–2.3 (–3.5; –1.1), n = 19 pairs	–4.3 (–6.2; –2.4), n = 16 pairs
Paired change in cumulative ODI score (95% CI)		–12.0 (–15.1; –8.9), n = 55 pairs	–17.6 (–21.6; –13.5), n = 39 pairs

Numeric rating scale for back pain (NRS/10) and Oswestry Disability Index (ODI/50) measures reported preoperatively and postoperatively at 6 wk and 1 yr. Bold values indicate a statistically significant difference from preoperative baseline in PROs, $P < .001$.

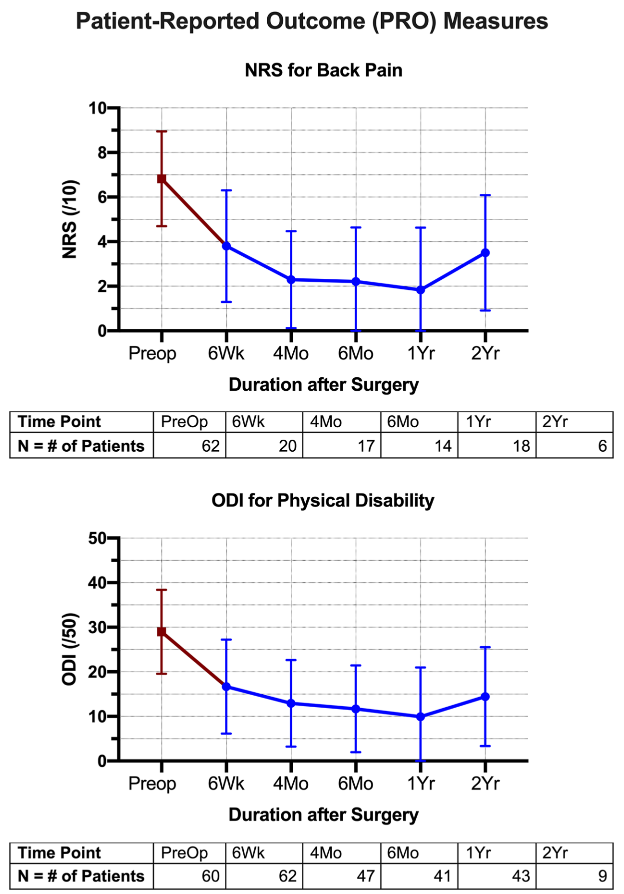


FIGURE 2. *Longitudinal data exploring patient-reported outcome measures obtained preoperatively and during routine postoperative clinic visits following transfacet MIS-TLIF. The smoothed lines represent the mean PRO measure scores. The error bars represent SD in both directions. NRS: Numeric Rating Scale for low back pain (/10). ODI: Oswestry Disability Index for physical disability (/50).*

postoperatively and 10.0 (SD 11.0) at 1 yr. Among patients with paired preoperative and either 6-wk or 1-yr postoperative ODI, 22/55 (40.0%) and 22/39 (56.4%) achieved the MCID threshold of 12.8 points, respectively.

Radiographic Outcomes

Index-Level Segmental Parameters

Transfacet MIS-TLIF with an expandable interbody device was associated with immediate and sustained increases in index-level DH, FH, and SL (Table 3 and Figure 3). Mean DH increased significantly from 0.95 cm (SD 0.3) preoperatively to 1.69 cm (SD 0.2) immediately postoperatively and was 1.67 cm (SD 0.3) on the last follow-up. Similarly, FH increased from 1.98 cm (SD 0.3) to 2.25 cm (SD 0.3) immediately following surgery and was sustained at 2.25 cm (SD 0.3) late postoperatively. There was an immediate and large increase in SL from 6.95° (SD 4.0) preoperatively to 14.12° (SD 3.2) postoperatively (mean paired change 6.83°, 95% CI 5.8; 7.9). SL increases were maintained during late follow-up (mean paired change 5.98°, 95% CI 4.9; 7.0).

There was a sustained postoperative reduction in spondylolisthesis. Prior to surgery, 61/73 (82.4%) operative levels had grade I spondylolisthesis, and the remaining 12/73 (16.2%) were grade II (>25% slip). The mean percentage offset of one vertebral body over its adjacent segment corrected significantly from 17.15% (SD 8.1) to 7.15% (SD 3.8) immediately and 9.14% (SD 5.2) late postoperatively.

OLL and Pelvic Parameters

Paired differences between preoperative and each "immediate" or "late" postoperative measurements of OLL, PI-OLL mismatch, PT, and SS angle were not statistically significant (Table 3 and Figure 4). Preoperative OLL was 53.99° (SD 12.1) and was not significantly increased immediately postoperatively (mean paired change 0.53°, 95% CI –1.9; 3.0). Late postoperative OLL was minimally increased from baseline (mean paired change 2.81°, 95% CI 0.6; 5.0).

Transfacet MIS-TLIF had nominal effects on pelvic parameters. SS was not significantly increased from the preoperative mean value of 37.08° (SD 9.6) immediately (mean paired change 1.58°, 95% CI–0.2; 3.4) or late (mean paired change 0.43°, 95% CI–1.5; 2.4) postoperatively. Similarly, for PT (preoperative 20.35°, SD 9.4) at the immediate (mean paired change 0.26°, 95% CI–2.1; 2.6) and late (mean paired change 0.28°, 95% CI–2.3; 2.9) postoperative follow-up.

TABLE 3. Radiographic Outcomes after MIS-TLIF, Reported Preoperatively and During "Immediate" (Day 1) and "Late" (Last Available) Postoperative Follow-up

Radiographic outcomes by operative state, mean (SD)	Preoperative (N = 67 patients, 73 levels)	Immediate postoperative (N = 61 patients, 65 levels)	Late postoperative (N = 67 patients, 73 levels)
Segmental parameters			
Disc height, cm	0.95 (0.3)	1.69 (0.2)	1.67 (0.3)
Change in disc height (95% CI)		**0.71 (0.6; 0.8)**	**0.71 (0.6; 0.8)**
Foraminal height, cm	1.98 (0.3)	2.25 (0.3)	2.25 (0.3)
Change in foraminal height (95% CI)		**0.28 (0.2; 0.4)**	**0.27 (0.2; 0.4)**
Segmental lordosis, °	6.95 (4.0)	14.12 (3.2)	13.09 (3.8)
Change in segmental lordosis (95% CI)		**6.83 (5.8; 7.9)**	**5.98 (4.9; 7.0)**
Spondylolisthesis, %	17.15 (8.1)	7.15 (3.8)	9.14 (5.2)
Change in spondylolisthesis (95% CI)		**−9.12 (−11.1; −7.2)**	**−7.77 (−9.7; −5.9)**
Regional lumbopelvic parameters			
Overall lumbar lordosis (OLL), °	53.99 (12.1)	54.85 (10.3)	57.05 (12.0)
Change in OLL (95% CI)		0.53 (−1.9; 3.0)	**2.81 (0.6; 5.0)**
Pelvic incidence (PI), °	57.43 (11.1)	59.72 (13.1)	58.39 (12.3)
Change in PI (95% CI)		1.84 (−0.9; 4.5)	0.71 (−1.8; 3.2)
PI-OLL mismatch, °	9.61 (7.6)	9.03 (6.6)	7.88 (5.8)
Change in PI-OLL mismatch (95% CI)		−0.42 (−2.4; 1.6)	−1.71 (−4.0; 0.5)
Sacral slope angle, °	37.08 (9.6)	39.08 (9.4)	37.85 (9.2)
Change in sacral slope angle (95% CI)		1.58 (−0.2; 3.4)	0.43 (−1.5; 2.4)
Pelvic tilt, °	20.35 (9.4)	20.65 (8.7)	20.53 (10.0)
Change in pelvic tilt (95% CI)		0.26 (−2.1; 2.6)	0.28 (−2.3; 2.9)

Bold values indicated statistically significant paired differences in radiographic outcomes between preoperative and the corresponding postoperative time point, $P < .05$.

Stratification by Preoperative Regional Lumbar Lordosis

We performed a stratified analysis of changes in SL, OLL, and pelvic parameters based on preoperative OLL in 3 strata (Table 4).

We observed significant postoperative increases in SL within each OLL subgroup. The magnitude of SL change was greater in patients with preoperative hypolordosis (mean paired change "immediate" 9.10°, SD 2.3; and "late" 6.82°, SD 4.3) than those with hyperlordosis (mean paired change "immediate" 5.97°, SD 5.0; and "late" 5.82°, SD 5.0). Moreover, patients with preoperative hypolordosis experienced significant and large increases in OLL (mean paired change "immediate" 8.65°, SD 5.3; and "late" 9.74°, SD 9.9). Individuals who were hyperlordotic at baseline, despite increases in SL, experienced a mean decrease in OLL (mean paired change "immediate" –4.77°, SD 9.5; and "late" –1.06°, SD 6.6). We did not observe meaningful changes in pelvic parameters within OLL subgroups.

Linear regression revealed a significant inverse relationship between preoperative SL and postoperative change in SL ("immediate" $r^2 = 0.48$ and "late" $r^2 = 0.38$) (Figure 5). There was a similar inverse relationship between preoperative OLL and change in OLL ("immediate" $r^2 = 0.34$ and "late" $r^2 = 0.16$), wherein a low preoperative OLL was associated with a greater postoperative increase in OLL, as was seen in the stratified analysis (Figure 6).

Pseudarthrosis and Interbody Device Subsidence

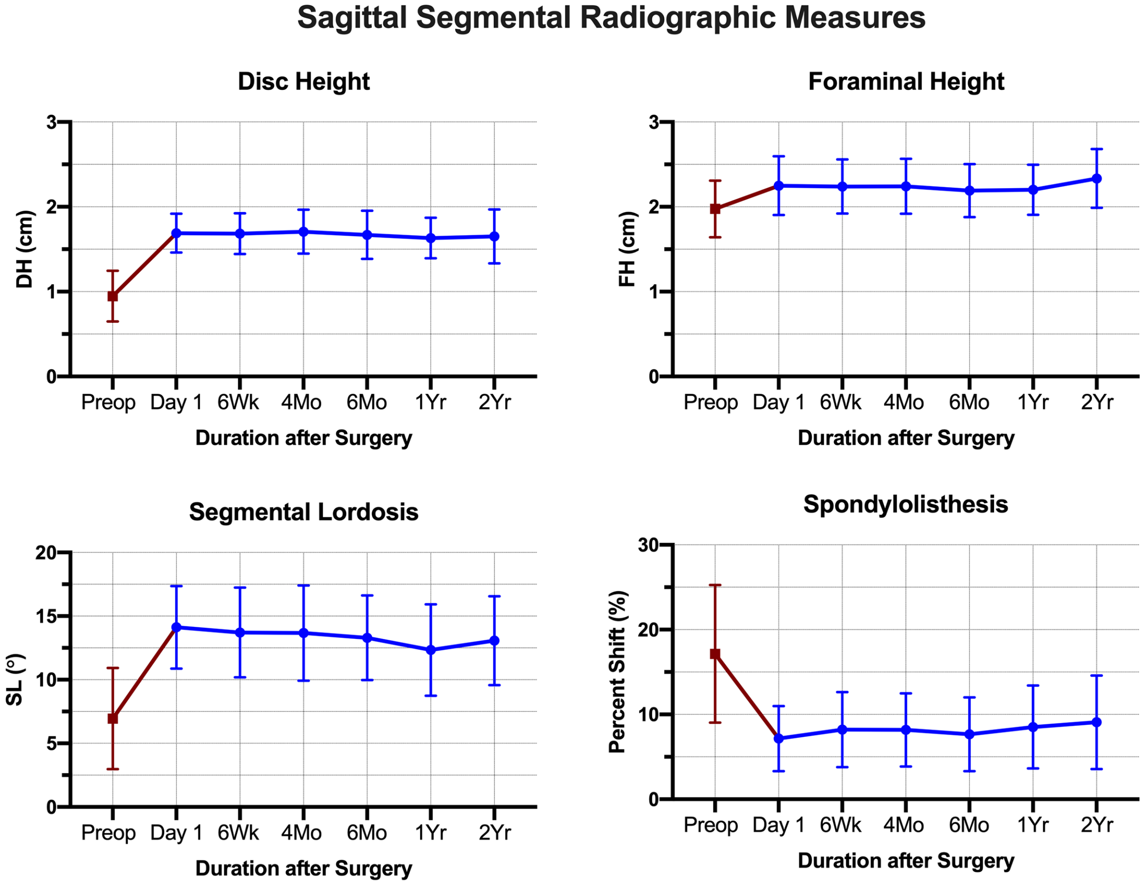
Of the 49 patients with radiographic follow-up at least 12 mo postoperatively, 3/49 (6.1%) had signs of radiographic pseudarthrosis at 3/53 (5.7%) levels. None of the 3 patients with radiographic pseudarthrosis experienced new or worsening symptoms of low back or leg pain requiring revision surgery.

Radiographic subsidence was observed in 6/68 (8.8%) patients at 6/74 (8.1%) levels. One of the 6 patients had marked subsidence into the endplate of the caudal vertebral body and required revision anterior fusion surgery within 6 wk of *transfacet* MIS-TLIF (Figure 7). Two of the 6 patients with early subsidence progressed to radiographic pseudarthrosis.

DISCUSSION

Summary of the Findings

In summary, patients with degenerative lumbar spondylolisthesis who underwent *transfacet* MIS-TLIF with placement of expandable interbody devices experienced immediate and sustained improvements in clinical outcomes and radiographic sagittal segmental parameters. PRO measures for back-related pain and disability were improved during short- and long-term postoperative follow-up. The mean change from baseline was approximately –2 to –4/10 points on the NRS back pain and –12 to –18/50 points on the ODI. Most patients exceeded



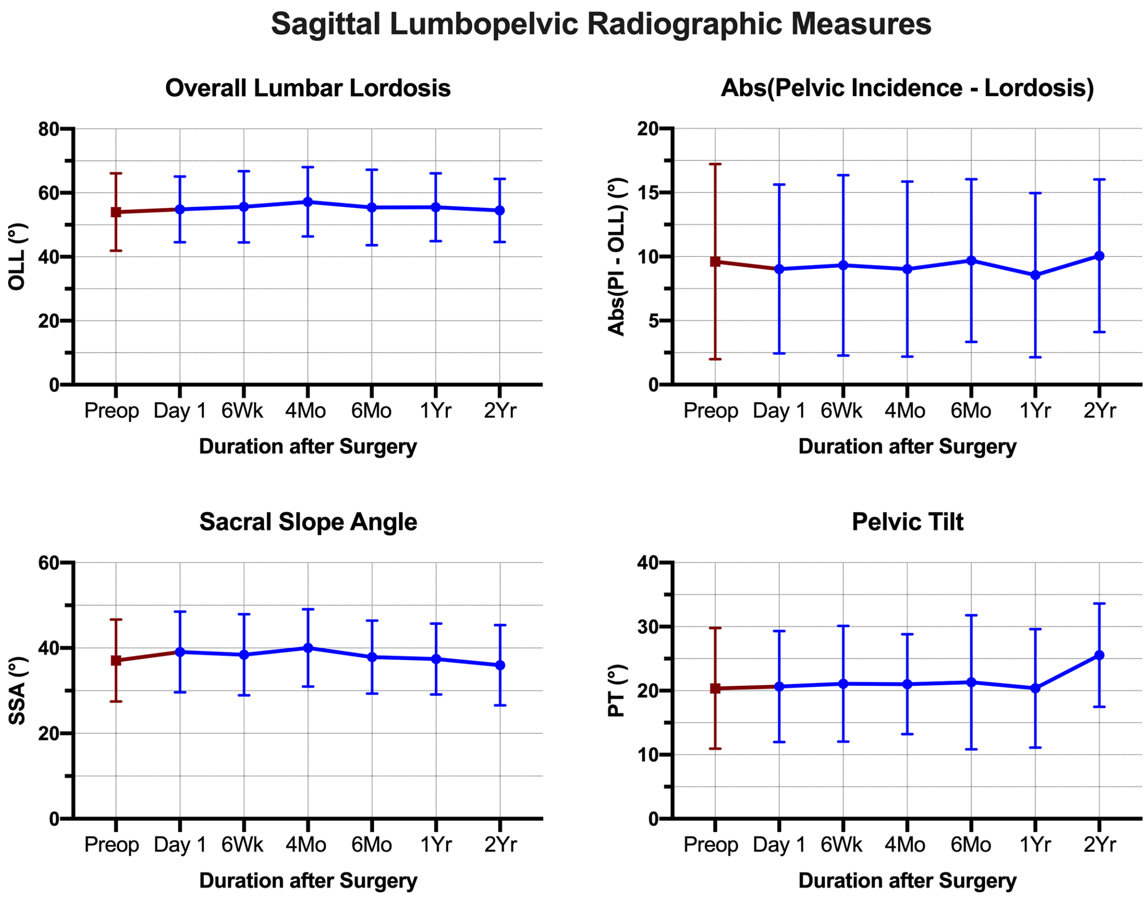
Time Point	PreOp	Day 1	6Wk	4Mo	6Mo	1Yr	2Yr
N = # of Patients	67	61	65	56	51	44	17
N = # of Levels	73	65	70	61	56	47	17

FIGURE 3. *Longitudinal data exploring the repeated sagittal segmental radiographic measurements before and after transfacet MIS-TLIF. The smoothed lines represent the mean radiographic profiles. The error bars represent SD in both directions.*

the estimated MCID thresholds for these PRO measures. We observed immediate and sustained increases in index-level anterior DH (∼0.7 cm), FH (∼0.3 cm), and SL (∼6°). *Transfacet* MIS-TLIF was not associated with clinically meaningful increases in OLL (0.5°-3°). However, our stratified analysis showed significant differences between strata by preoperative OLL, suggesting that the variance in segmental and regional lordotic changes is explained by baseline radiographic factors. Specifically, preoperative hypolordosis was associated with large positive corrections in SL and OLL.

Findings in Context: MIS-TLIF With an Expandable Interbody Device

The use of expandable interbody devices provides additional sagittal segmental correction when compared with historical data on MISS lumbar fusions using static devices. Several studies examine the effects of device type on radiographic sagittal segmental parameters after open or MIS-TLIF. Yee et al[38] showed that patients undergoing TLIF experienced marginal increases in SL, regardless of whether expandable (1°-2°) or static (3°) devices were used. However, in a radiographic analysis by Hawasli et al,[14] patients who underwent MIS-TLIF with expandable versus static devices demonstrated larger increases in index-level DH (0.82 vs 0.26 cm), FH (0.13 vs 0.05 cm), and SL (5.2° vs 2.3°). Kim et al[15] and Massie et al[11] found similar results in favor of expandable devices. We did not perform a direct comparison by device type. However, we speculate that expandable devices may add greater DH and SL to widen the interpedicular distance, as compared to static devices, with no meaningful difference in endplate subsidence or fusion.



Time Point	PreOp	Day 1	6Wk	4Mo	6Mo	1Yr	2Yr
N = # of Patients	67	61	65	56	51	44	17

FIGURE 4. *Longitudinal data exploring the repeated sagittal lumbopelvic radiographic measurements before and after transfacet MIS-TLIF. The smoothed lines represent the mean radiographic profiles. The error bars represent SD in both directions.*

Our results compare favorably with published radiographic and clinical outcomes after MIS-TLIF using crescent-shaped articulating expandable interbody devices. In a retrospective cohort of 44 patients who underwent MIS-TLIF at 49 levels and 1.5 yr median follow-up, Massie et al[11] reported significant clinical improvements of –3.3/10 on the NRS back pain and –15.7/50 on the ODI. They observed significant changes in sagittal segmental parameters, specifically increases of 4.94° in SL and 0.31 cm in posterior DH, and a reduction of 0.43 cm in spondylolisthesis. They did not observe significant increases in spinopelvic parameters of sagittal vertical axis or PT. In our study, spinopelvic parameters of PI-OLL mismatch, SS angle, and PT were not significantly changed. We did not expect to see differences in overall sagittal balance as the majority (83.8%) of *transfacet* MIS-TLIF were single level. Moreover, additional reconstruction via anterior column realignment, posterior column osteotomy, or sacral/pelvic osteotomy was not performed.

Findings in Context: Local and Regional Sagittal Balance After MISS

The restoration of local and regional sagittal balance is an important consideration after MISS. In a literature review comprising 1182 patients from 24 anterior, lateral, and posterior/transforaminal MISS lumbar interbody fusion study cohorts (6 studies examining MIS-TLIF), Uribe et al[18] reported a 3.9° increase in SL, from an average 8.1° preoperatively to 12.0° postoperatively. In a subsequent systematic review, Carlson et al[22] identified 9 studies that reported segmental (SL) and regional (OLL) lordotic changes after MIS-TLIF. The mean preoperative SL was 12.7° and postoperative SL was 15°, an increase

TABLE 4. Radiographic Outcomes Stratified by Preoperative Regional Overall Lumbar Lordosis (OLL)

Radiographic outcomes by lordotic stratification, Mean (SD)	Hypolordosis (N = 10 patients, 10 levels)	Normolordosis (N = 35 patients, 40 levels)	Hyperlordosis (N = 22 patients, 23 levels)	One-way ANOVA *P* value
Preoperative				
Segmental lordosis (SL), °	4.15 (2.0)	7.08 (3.9)	7.93 (4.3)	**.038**
Overall lumbar lordosis (OLL), °	34.16 (5.3)	51.42 (5.6)	67.09 (4.2)	**<.001**
Pelvic incidence (PI), °	49.08 (11.1)	55.9 (10.2)	63.66 (9.3)	**.001**
PI-OLL mismatch, °	14.92 (9.5)	9.41 (7.6)	7.51 (5.6)	**.035**
Sacral slope angle, °	26.81 (6.9)	35.55 (8.1)	44.18 (7.5)	**<.001**
Pelvic tilt, °	22.28 (7.5)	20.35 (8.5)	19.48 (11.7)	.745
Immediate postoperative				
SL	13.07 (2.5)	14.27 (3.6)	14.18 (3.0)	.613
Change in SL (95% CI)	**9.10 (7.4; 10.8)**	**6.78 (5.4; 8.2)**	**5.97 (3.8; 8.2)**	.180
OLL	42.41 (5.3)	53.08 (5.5)	62.21 (11.1)	<.001
Change in OLL (95% CI)	**8.65 (4.6; 12.8)**	1.81 (–1.3; 5.0)	**–4.77 (–9.1; –0.5)**	**.001**
PI	53.47 (11.5)	56.49 (11.6)	66.36 (13.3)	**.008**
Change in PI (95% CI)	5.17 (–1.4; 11.7)	0.82 (–2.7; 4.3)	1.86 (–3.9; 7.6)	.557
PI-OLL mismatch	11.88 (6.4)	9.39 (7.3)	7.32 (5.5)	.210
Change in PI-OLL (95% CI)	–2.66 (–9.6; 4.2)	–0.44 (–3.3; 2.5)	0.57 (–2.9; 4.0)	.590
Sacral slope	31.26 (5.6)	36.83 (8.2)	45.0 (8.8)	**<.001**
Change in sacral slope (95% CI)	**4.74 (1.5; 8.0)**	0.85 (–1.6; 3.3)	1.25 (–2.5; 5.0)	.334
Pelvic tilt	22.21 (6.3)	19.65 (9.1)	21.36 (9.2)	.673
Change in pelvic tilt (95% CI)	0.43 (–5.6; 6.4)	–0.03 (–3.3; 3.3)	0.61 (–4.2; 5.5)	.970
Late postoperative				
SL	10.97 (3.0)	13.03 (4.0)	13.75 (3.3)	**.144**
Change in SL (95% CI)	**6.82 (3.8; 9.9)**	**5.86 (4.5; 7.3)**	**5.82 (3.7; 8.0)**	.817
OLL	43.90 (10.7)	54.51 (9.0)	66.03 (8.8)	**<.001**
Change in OLL (95% CI)	**9.74 (2.7; 16.8)**	**3.27 (0.2; 6.3)**	–1.06 (–4.0; 1.8)	**.004**
PI	48.21 (8.8)	57.55 (11.0)	63.35 (12.3)	**.003**
Change in PI (95% CI)	–0.87 (–6.5; 4.8)	1.84 (–1.9; 5.5)	–0.31 (–5.1; 4.5)	.654
PI-OLL mismatch	5.05 (4.5)	8.09 (6.0)	9.12 (5.8)	.186
Change in PI-OLL (95% CI)	**–9.87 (–18.5; –1.2)**	–1.45 (–4.3; 1.3)	1.61 (–1.6; 4.8)	**.003**
Sacral slope	31.10 (8.2)	35.01 (7.2)	44.33 (7.4)	**<.001**
Change in sacral slope (95% CI)	4.29 (–0.01; 8.6)	–0.52 (–3.3; 2.3)	0.15 (–3.5; 3.8)	.236
Pelvic tilt	17.11 (3.9)	22.54 (9.5)	19.02 (12.3)	.226
Change in pelvic tilt (95% CI)	**–5.16 (–9.9; –0.4)**	2.36 (–1.0; 5.7)	–0.46 (–6.1; 5.2)	.130

One-way ANOVA performed to compare the 3 lordosis groups. Bold values indicate significant differences, $P < .05$.

of 2.1°. Change in SL ranged between 0.1° and 8.4°, with most reports between 0° and 3°. This is slightly lower than observed in our series. Notably, the majority (111/171, 65%) of included cases in the systematic review used static interbody devices, which may provide less lordotic restoration than expandable interbody devices.[11,14] The authors were cautious in their interpretation because of marked variability within the literature in the measurement and reporting of radiographic parameters.

Regional (OLL) lordotic changes after MISS lumbar interbody fusions are influenced by multiple factors, including operative levels, number of levels treated, interbody device position, device type, internal fixation, and use of compressive techniques.[18] In a systematic review of 19 MISS lumbar interbody fusion cohorts and 720 patients, Uribe et al[18] reported a significant increase of 3.7° in OLL, from an average 43.5° preoperatively to 47.2° postoperatively. For MIS-TLIF specifically, the systematic review by Carlson et al[22] reported a mean increase in OLL from 39.6° to 45.0°, corresponding to a pre-post difference of 5.2°. However, OLL change estimates varied considerably, ranging from –6.8° to 14.7°, with most studies reporting minimal increases between 1° and 7°.

Segmental (SL) and regional (OLL) lordotic changes may be explained by variation in preoperative lordosis. In the previously mentioned report, Uribe et al[18] found a significant inverse relationship between preoperative OLL and postoperative change in OLL ($r^2 = 0.41$), whereas SL did not have a similar association ($r^2 = 0.001$). Using pooled data from a systematic review, Carlson et al[22] found that preoperative SL (B = 0.58) and OLL (B = –0.13), and postoperative OLL (B = 0.21) were associated with increased postoperative SL. In our study, linear regression revealed significant associations between each

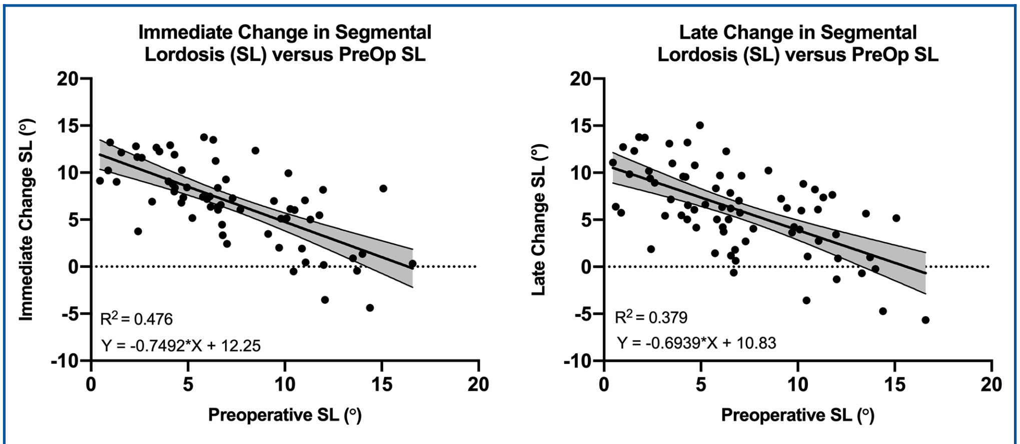


FIGURE 5. *Scatterplots of postoperative "immediate" and "late" changes in segmental lordosis (SL) vs preoperative values of SL. Ordinary least squares (OLS) regression lines and 95% CI included.*

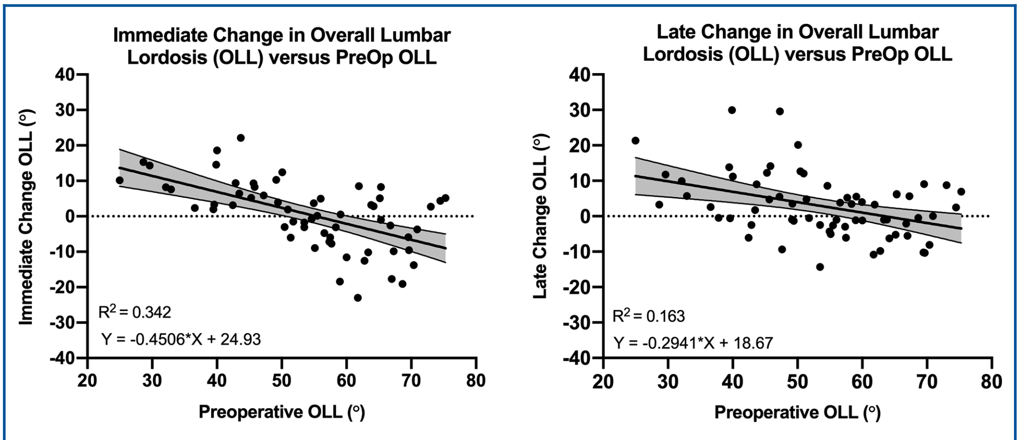


FIGURE 6. *Scatterplots of postoperative "immediate" and "late" changes in regional overall lumbar lordosis (OLL) vs preoperative values of OLL. Ordinary least squares (OLS) regression lines and 95% CI included.*

preoperative SL ("immediate" change $r^2 = 0.48$ and "late" change $r^2 = 0.38$) and OLL ("immediate" change $r^2 = 0.34$ and "late" change $r^2 = 0.16$) and their corresponding postoperative change values (Figures 5 and 6). Similarly, in our stratified analysis, preoperative hypolordosis (OLL < 40°) was associated with relatively large increases in OLL (mean change "immediate" 8.65° and "late" 9.74°). The association between preoperative SL and OLL and the corresponding change values is stronger than would be expected from regression towards the mean (see **Figures**, **Supplemental Digital Contents 1** and **2**). For these reasons, Uribe et al[18] make the distinction between alignment "preservation" and "restoration/correction." Alignment changes, particularly lordosis increases, are possible after MISS lumbar interbody fusion, even MIS-TLIF. However, the extent of correction gained largely depends on preoperative spinal lordosis.

Findings in Context: Interbody Fusion and Device Subsidence

Lastly, radiographic interbody fusion was observed in 94.3% (50/53) levels after 12 mo, and subsidence in 8.1% (6/74) of all included levels. In a meta-analysis by Parajón et al[6] of 40 reports and 1533 patients, fusion rates for MIS-TLIF were high, ranging from 91.8% to 99.1%, regardless of graft material. At a minimum follow-up of 12 mo, fusion rates for patients treated with (32.6% of patients) and without (67.4% of patients) recombinant human bone morphogenic protein were 98.8% and 93.1%, respectively. In the report by Massie et al,[11] in which titanium expandable interbody devices were used, fusion rate was 96% (46/48 levels) at 12 mo. The subsidence rate was 6.1% (3/49), and none of the cases were clinically significant nor required revision surgery. Although these results are reassuring, well-powered, prospective studies with extended follow-up are needed to estimate the risks

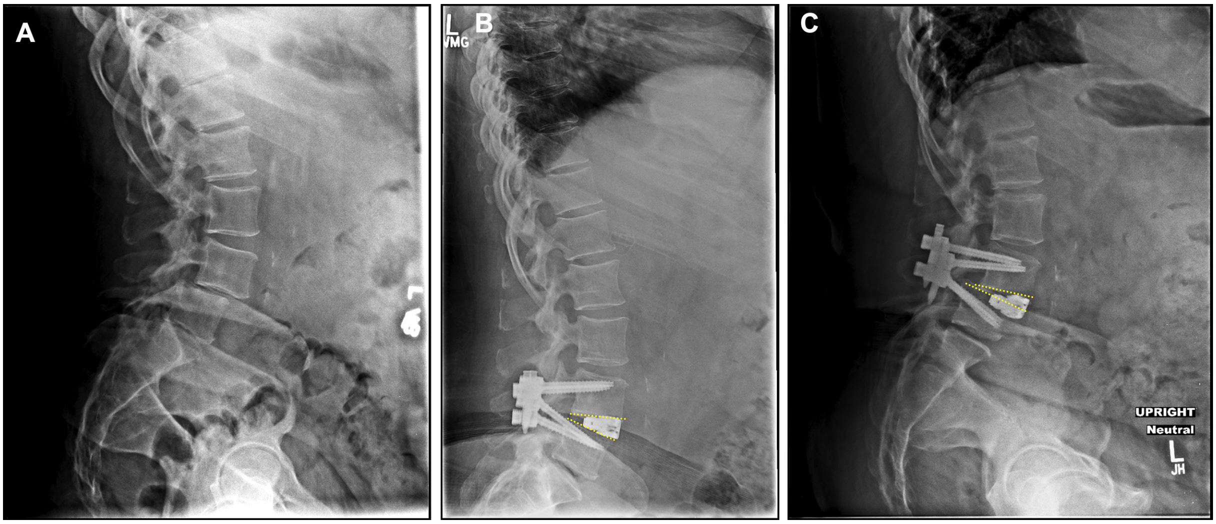


FIGURE 7. *Upright lateral radiographs taken* **A**, *preoperatively,* **B**, *postoperatively on day 1, and* **C**, *6 wk following transfacet MIS-TLIF at L4-L5. Radiograph at 6 wk shows subsidence of the expandable interbody device into the caudal endplate and new grade II anterolisthesis of L4 on L5. The patient subsequently underwent revision surgery with removal of the posterior instrumentation, followed by anterior lumbar interbody fusion.*

of long-term complications with expandable devices, including adjacent segment disease, subsidence, and pseudarthrosis.

Limitations of the Study

Our study has several important limitations. First, this is a single-center observational study with a relatively small sample size, variable follow-up, and some missing data. Second, this study is limited by lack of a comparator group, namely standard MIS-TLIF, against which to compare clinical outcomes and radiographic results. Third, radiographic results are subject to measurement error because of variable radiograph quality and inaccuracy because of observer errors. Moreover, as it is not possible to blind reviewers to a patient's operative state, measurements made on postoperative radiographs may be systematically biased to favorable changes in sagittal parameters. The effects of random and systematic measurement error were mitigated by the use of standard procedures for outcomes assessment, blinding of reviewers to PROs, and serial postoperative measurements by 2 independent reviewers.

CONCLUSION

Patients undergoing *transfacet* MIS-TLIF with expandable interbody devices experienced clinically meaningful improvements in PROs. Radiographic sagittal segmental parameters of SL, anterior DH, FH, and spondylolisthesis were improved early following *transfacet* MIS-TLIF and were sustained throughout the postoperative course. *Transfacet* MIS-TLIF did not affect OLL or spinopelvic parameters (PI-OLL, SS, and PT); however, it was associated with significant regional lordotic alignment corrections among patients with low baseline OLL ($<40°$). Patients had acceptable rates of interbody fusion and device subsidence consistent with those reported in the literature.

Disclosures

The authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article. Dr Ray is a consultant for DePuy/Synthes and Globus Spine. Dr Hawasli is a consultant for DePuy/Synthes and Johnson & Johnson. Dr Dorward is a consultant for Medtronic and Stryker.

REFERENCES

1. Yoon JW, Wang MY. The evolution of minimally invasive spine surgery: JNSPG 75th Anniversary Invited Review Article. *J Neurosurg Spine*. 2019;30(2):149-158.
2. Khan NR, Clark AJ, Lee SL, Venable GT, Rossi NB, Foley KT. Surgical outcomes for minimally invasive vs open transforaminal lumbar interbody fusion. *Neurosurgery*. 2015;77(6):847-874; discussion 874.
3. Brodano GB, Martikos K, Lolli F, et al. Transforaminal lumbar interbody fusion in degenerative disk disease and spondylolisthesis grade I. *J Spinal Disord Tech*. 2015;28(10):E559-E564.
4. Peng CW, Yue WM, Poh SY, Yeo W, Tan SB. Clinical and radiological outcomes of minimally invasive versus open transforaminal lumbar interbody fusion. *Spine*. 2009;34(13):1385-1389.
5. Shunwu F, Xing Z, Fengdong Z, Xiangqian F. Minimally invasive transforaminal lumbar interbody fusion for the treatment of degenerative lumbar diseases. *Spine*. 2010;35(17):1615-1620.
6. Parajon A, Alimi M, Navarro-Ramirez R, et al. Minimally invasive transforaminal lumbar interbody fusion: meta-analysis of the fusion rates. What is the optimal graft material? *Neurosurgery*. 2017;81(6):958-971.
7. Wu RH, Fraser JF, Hartl R. Minimal access versus open transforaminal lumbar interbody fusion. *Spine*. 2010;35(26):2273-2281.
8. Choi WS, Kim JS, Hur JW, Seong JH. Minimally invasive transforaminal lumbar interbody fusion using banana-shaped and straight cages: radiological and clinical results from a prospective randomized clinical trial. *Neurosurgery*. 2018;82(3):289-298.

9. Guan J, Bisson EF, Dailey AT, Hood RS, Schmidt MH. Comparison of clinical outcomes in the national neurosurgery quality and outcomes database for open versus minimally invasive transforaminal lumbar interbody fusion. *Spine*. 2016;41(7):E416-E421.
10. Yoshihara H. Indirect decompression in spinal surgery. *J Clin Neurosci*. 2017;44:63-68.
11. Massie LW, Zakaria HM, Schultz LR, Basheer A, Buraimoh MA, Chang V. Assessment of radiographic and clinical outcomes of an articulating expandable interbody cage in minimally invasive transforaminal lumbar interbody fusion for spondylolisthesis. *Neurosurg Focus*. 2018;44(1):E8.
12. Hunt T, Shen FH, Arlet V. Expandable cage placement via a posterolateral approach in lumbar spine reconstructions. *J Neurosurg Spine*. 2006;5(3):271-274.
13. Boktor JG, Pockett RD, Verghese N. The expandable transforaminal lumbar interbody fusion - two years follow-up. *J Craniovertebr Junction Spine*. 2018;9(1):50-55.
14. Hawasli AH, Khalifeh JM, Chatrath A, Yarbrough CK, Ray WZ. Minimally invasive transforaminal lumbar interbody fusion with expandable versus static interbody devices: radiographic assessment of sagittal segmental and pelvic parameters. *Neurosurg Focus*. 2017;43(2):E10.
15. Kim CW, Doerr TM, Luna IY, et al. Minimally invasive transforaminal lumbar interbody fusion using expandable technology: a clinical and radiographic analysis of 50 patients. *World Neurosurg*. 2016;90:228-235.
16. Kawakami M, Tamaki T, Ando M, Yamada H, Hashizume H, Yoshida M. Lumbar sagittal balance influences the clinical outcome after decompression and posterolateral spinal fusion for degenerative lumbar spondylolisthesis. *Spine*. 2002;27(1):59-64.
17. Glassman SD, Bridwell K, Dimar JR, Horton W, Berven S, Schwab F. The impact of positive sagittal balance in adult spinal deformity. *Spine*. 2005;30(18):2024-2029.
18. Uribe JS, Myhre SL, Youssef JA. Preservation or restoration of segmental and regional spinal lordosis using minimally invasive interbody fusion techniques in degenerative lumbar conditions: a literature review. *Spine (Phila Pa 1976)*. 2016;41(suppl 8):S50-S58.
19. Schwab F, Patel A, Ungar B, Farcy JP, Lafage V. Adult spinal deformity: postoperative standing imbalance. *Spine*. 2010;35(25):2224-2231.
20. Than KD, Park P, Fu KM, et al. Clinical and radiographic parameters associated with best versus worst clinical outcomes in minimally invasive spinal deformity surgery. *J Neurosurg Spine*. 2016;25(1):21-25.
21. Rhee C, Visintini S, Dunning CE, Oxner WM, Glennie RA. Does restoration of focal lumbar lordosis for single level degenerative spondylolisthesis result in better patient-reported clinical outcomes? A systematic literature review. *J Clin Neurosci*. 2017;44:95-100.
22. Carlson BB, Saville P, Dowdell J, et al. Restoration of lumbar lordosis after minimally invasive transforaminal lumbar interbody fusion: a systematic review. *Spine J*. 2019;19(5):951-958.
23. Pereira C, Santos Silva P, Cunha M, Vaz R, Pereira P. How does minimally invasive transforaminal lumbar interbody fusion influence lumbar radiologic parameters? *World Neurosurg*. 2018;116:e895-e902.
24. Lau D, Song Y, Guan Z, La Marca F, Park P. Radiological outcomes of static vs expandable titanium cages after corpectomy. *Neurosurgery*. 2013;72(4):529-539; discussion 528-529.
25. Crandall DG, Chung AS, Lara N, Revella J. Risk factors for expandable cage subsidence in patients undergoing transforaminal lumbar interbody fusion. *Spine J*. 2017;17(10):S188-S189.
26. Arts MP, Peul WC. Vertebral body replacement systems with expandable cages in the treatment of various spinal pathologies. *Neurosurgery*. 2008;63(3):537-545; discussion 544-535.
27. Le TV, Baaj AA, Dakwar E, et al. Subsidence of polyetheretherketone intervertebral cages in minimally invasive lateral retroperitoneal transpsoas lumbar interbody fusion. *Spine*. 2012;37(14):1268-1273.
28. Marchi L, Abdala N, Oliveira L, Amaral R, Coutinho E, Pimenta L. Radiographic and clinical evaluation of cage subsidence after stand-alone lateral interbody fusion. *J Neurosurg Spine*. 2013;19(1):110-118.
29. Heary RF, Parvathreddy N, Sampath S, Agarwal N. Elastic modulus in the selection of interbody implants. *J Spine Surg*. 2017;3(2):163-167.
30. Copay AG, Glassman SD, Subach BR, Berven S, Schuler TC, Carreon LY. Minimum clinically important difference in lumbar spine surgery patients: a choice of methods using the Oswestry Disability Index, Medical Outcomes Study questionnaire Short Form 36, and pain scales. *Spine J*. 2008;8(6):968-974.
31. Hawasli AH, Chang J, Yarbrough CK, Steger-May K, Lenke LG, Dorward IG. Interpedicular height as a predictor of radicular pain in adult degenerative scoliosis. *Spine J*. 2016;16(9):1070-1078.
32. Timon SJ, Gardner MJ, Wanich T, et al. Not all spondylolisthesis grading instruments are reliable. *Clin Orthop Relat Res*. 2005;434:157-162.
33. Wiltse LL, Winter RB. Terminology and measurement of spondylolisthesis. *J Bone Joint Surg*. 1983;65(6):768-772.
34. O'Brien M, Kuklo T, Blanke K, Lenke L. *Spinal Deformity Study Group Radiographic Measurement Manual*. Memphis: Medtronic Sofamor Danek 2008.
35. Legaye J, Duval-Beaupere G, Hecquet J, Marty C. Pelvic incidence: a fundamental pelvic parameter for three-dimensional regulation of spinal sagittal curves. *Eur Spine J*. 1998;7(2):99-103.
36. Selby MD, Clark SR, Hall DJ, Freeman BJ. Radiologic assessment of spinal fusion. *J Am Acad Orthop Surg*. 2012;20(11):694-703.
37. Matthews JN, Altman DG, Campbell MJ, Royston P. Analysis of serial measurements in medical research. *BMJ*. 1990;300(6719):230-235.
38. Yee TJ, Joseph JR, Terman SW, Park P. Expandable vs static cages in transforaminal lumbar interbody fusion: radiographic comparison of segmental and lumbar sagittal angles. *Neurosurgery*. 2017;81(1):69-74.

Supplemental digital content *is available for this article at www.operativeneurosurgery-online.com*

Supplemental Digital Content 1. Figure. Scatterplots of change in regional segmental lordosis (SL) across a given time period vs SL at the beginning of that period. Boxed panel presents the change in SL following *transfacet* MIS-TLIF vs preoperative SL. Nonboxed panels present the change in SL across time periods in which no spinal surgical intervention was performed. The magnitude of the inverse relationship diminishes across time periods that do not span the operative event. This suggests that the association between change in SL after MIS-TLIF and preoperative SL is beyond what is expected because of regression towards the mean.

Supplemental Digital Content 2. Figure. Scatterplots of change in regional overall lumbar lordosis (OLL) across a given time period vs OLL at the beginning of that period. Boxed panel presents the change in OLL following *transfacet* MIS-TLIF vs preoperative OLL. Nonboxed panels present the change in OLL across time periods in which no spinal surgical intervention was performed. The magnitude of the inverse relationship diminishes across time periods that do not span the operative event. This suggests that the association between change in OLL after MIS-TLIF and preoperative OLL is beyond what is expected because of regression towards the mean (ie, towards normal ranges of overall lordosis).

COMMENT

The authors have presented their initial experience with the transfacet approach to MIS-TLIF using an expandable interbody device. The details of the operative technique are published in a concurrent approach. These findings suggest that among patients with low-grade degenerative lumbar spondylolisthesis, transfacet MIS-TLIF was associated with significant improvement in patient reported outcomes (NRS-BP and ODI). Moreover, the authors noted significant improvement in index-level segmental radiographic parameters like disc height, foraminal height and segmental lordosis, without significant change in overall lumbar lordosis. The rates of pseudarthrosis and cage subsidence were 6% and 8.8% respectively. Strengths of the study include standardized outcomes assessment, blinded radiographic evaluation and analysis stratified by preoperative lumbar lordosis.

The lack of comparison with standard MIS-TLIF and the variable length of follow up are the two most important limitations of this study. The outcomes observed seem to be congruent with previously available literature evaluating standard MIS-TLIF with expandable cages. In addition, as the authors correctly pointed out, it is important to contextualize the findings to use of an expandable cage which may itself be responsible for the improvements observed. Studies that involve comparison with standard MIS-TLIF would be welcome investigations for the future.

Mohamad Bydon
Rochester, Minnesota

PAGE INTENTIONALLY LEFT BLANK

PAGE INTENTIONALLY LEFT BLANK

PAGE INTENTIONALLY LEFT BLANK