





Predictors of Postoperative Segmental and Overall Lumbar Lordosis in Minimally Invasive Transforaminal Lumbar Interbody Fusion: A Consecutive Case Series

Global Spine Journal
2025, Vol. 15(2) 425–437
© The Author(s) 2023
Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/21925682231193610
journals.sagepub.com/home/gsj



Justin K. Zhang, MD, MSCI^{1,2} , Jacob K. Greenberg, MD, MSCI¹ , Saad Javeed, MD¹, Braeden Benedict, MS¹, Kathleen S. Botterbush, BS¹ , Christopher F. Dibble, MD, PhD¹, Jawad M. Khalifeh, MD, MSCI³, Samuel Brehm, BS¹, Deeptee Jain, MD⁴, Ian Dorward, MD¹, Paul Santiago, MD¹, Camilo Molina, MD¹, Brenton H. Pennicooke, MD¹ , and Wilson Z. Ray, MD¹

Abstract

Study Design: Retrospective Case-Series.

Objectives: Due to heterogeneity in previous studies, the effect of MI-TLIF on postoperative segmental lordosis (SL) and lumbar lordosis (LL) remains unclear. Therefore, we aim to identify radiographic factors associated with lordosis after surgery in a homogenous series of MI-TLIF patients.

Methods: A single-center retrospective review identified consecutive patients who underwent single-level MI-TLIF for grade I degenerative spondylolisthesis from 2015-2020. All surgeries underwent unilateral facetectomies and a contralateral facet release with expandable interbody cages. PROs included the ODI and NRS-BP for low-back pain. Radiographic measures included SL, disc height, percent spondylolisthesis, cage positioning, LL, PI-LL mismatch, sacral-slope, and pelvic-tilt. Surgeries were considered “lordosing” if the change in postoperative SL was $\geq +4^\circ$ and “kyphosing” if $\leq -4^\circ$. Predictors of change in SL/LL were evaluated using Pearson’s correlation and multivariable regression.

Results: A total of 73 patients with an average follow-up of 22.5 (range 12-61) months were included. Patients experienced significant improvements in ODI ($29\% \pm 22\%$ improvement, $P < .001$) and NRS-BP (3.3 ± 3 point improvement, $P < .001$). There was a significant increase in mean SL ($\Delta 3.43^\circ \pm 4.37^\circ$, $P < .001$) while LL ($\Delta 0.17^\circ \pm 6.98^\circ$, $P > .05$) remained stable. Thirty-eight (52%) patients experienced lordosing MI-TLIFs, compared to 4 (5%) kyphosing and 31 (43%) neutral MI-TLIFs. A lower preoperative SL and more anterior cage placement were associated with the greatest improvement in SL ($\beta = -.45^\circ$, $P = .001$, $\beta = 15.06^\circ$, $P < .001$, respectively).

Conclusions: In our series, the majority of patients experienced lordosing or neutral MI-TLIFs ($n = 69$, 95%). Preoperative radiographic alignment and anterior cage placement were significantly associated with target SL following MI-TLIF.

¹ Department of Neurological Surgery, Washington University, St. Louis, MO, USA

² Department of Neurosurgery, University of Utah, Salt Lake City, UT, USA

³ Department of Neurological Surgery, Johns Hopkins University, Baltimore, MD

⁴ Department of Orthopedic Surgery, Washington University, St. Louis, MO, USA

Corresponding Author:

Wilson Z. Ray, MD, Department of Neurological Surgery Washington University, St. Louis, MO, USA.

Email: rayz@wustl.edu



Creative Commons Non Commercial No Derivs CC BY-NC-ND: This article is distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs 4.0 License (<https://creativecommons.org/licenses/by-nc-nd/4.0/>) which permits non-commercial use, reproduction and distribution of the work as published without adaptation or alteration, without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (<https://us.sagepub.com/en-us/nam/open-access-at-sage>).

Keywords

transforaminal lumbar interbody fusion, minimally invasive, lumbar lordosis, segmental lordosis, spondylolisthesis, transforaminal lumbar interbody fusion

Introduction

The malaligned spine in short-segment, degenerative disease has shown to be associated with worse health-related quality-of-life assessments,¹ increased incidence of adjacent level spondylolisthesis,² elevated rates of construct failure, and adjacent segment disease.²⁻⁵ Described by Foley and Lefkowitz in 2002, minimally invasive transforaminal lumbar interbody fusion (MI-TLIF) has become a well-established procedure to address degenerative lumbar pathologies.⁶

In recent decades, the maintenance and correction of sagittal alignment has shown to be significantly associated with clinical outcomes and quality-of-life.¹ Consequently, there has been a growing body of literature discussing the effect of lumbar interbody fusion on radiographic outcomes.⁷ In the MI-TLIF literature, the extent of sagittal correction has come into question, with some studies suggesting a MI-TLIF is a kyphosing operation.^{6,8-14} However, previous studies often included heterogeneous patient populations without controlling for multiple confounders (e.g., cage type), limiting the interpretability of radiographic outcomes analyses following MI-TLIF.

With the increasing utilization of MI-TLIF, identifying predictors of sagittal alignment could help guide surgical decision making. Given conflicting reports in existing literature, we focused on a homogenous series of MI-TLIF patients, with indication, clinical, and operative details remaining constant. To this end, we investigated radiographic factors that determine MI-TLIF kyphosis or lordosis in patients undergoing single-level fusion for grade 1 spondylolisthesis with minimum 1-year follow up.

Methods

Study Design and Patient Population

We conducted a single-center, retrospective case series of consecutive patients who underwent MI-TLIF by a single spine surgeon from 2015-2020. Inclusion criteria included patients undergoing single-level surgery for grade 1 degenerative spondylolisthesis. Patients receiving expandable interbody devices undergoing unilateral facetectomies with a contralateral facet release were included. Multiple-level TLIF, revision TLIF, surgeries utilizing osteotomies, prior lumbar fusion at adjacent levels, or cases involving infection, tumor, or osteoporosis were excluded. This case series has been reported in line with the PROCESS Guideline¹⁵ and was approved by our university's IRB (IRB# 202004195). A waiver of consent was obtained.

Surgical Technique

All patients underwent unilateral facetectomies with a contralateral facet release using an osteotome and high-speed drill, along with bilateral pedicle screw fixation. Expandable interbody devices were placed, with the size, type, and lordotic angle chosen based on the surgeon's preference and patient anatomy. MI-TLIF surgeries were performed by a standard operative technique that has been previously described.¹⁶⁻²¹ Surgeries were performed on a modular ProAxis Jackson table (Mizuho), which would be oriented at the start of the case in a flexed position to facilitate the approach. Tiger Jamshidi needles (Stryker) and fluoroscopy were used for percutaneous pedicle screw insertion, and the MetRx sequential dilating tubular retractor system (Medtronic) was used to dilate down to the bilateral facet complex. Though there is mixed evidence regarding its impact on LL, bilateral facetectomies are a well-established and effective technique in MI-TLIF.^{1,9,17,22} At our institution, we typically perform a unilateral facetectomy with a contralateral facet release. This consisted of using electrocautery to disrupt the facet capsule, then placing a half inch straight osteotome on the facet and malleting until the joint could be felt to move. This joint was then packed with bone auto and allograft at the end of the case. When more substantial lordosis is needed, we generally pursued alternative interbody techniques (e.g., ALIF) or performed open TLIFs with extensive bilateral facetectomies. On the facetectomy side, the craniocaudal extent of the superior articulating process was exposed and drilled, with special attention to leave a portion of the medial inferior articulating process and pars intact to protect the thecal sac, and the traversing and exiting nerve roots. Bone shavings were collected for use as the autograft. Curettes and endplate shavers were used for the discectomy, with care to directly visualize the anterior annulus. In this study, either a straight or "bullet" cage or an articulating or "banana" cage was used. Our straight cages expanded after bone graft was packed whereas our articulating cages allowed for packing of bone graft after cage expansion. After endplate decortication, bone aspirate concentrate and allograft were packed into the anterior disc space. Then, an inserter was used to place a packed expandable interbody device into the disc space, with care to place the cage in the anterior annulus. Depending on the device type, allograft was also packed into the cage after expansion. After final rod placement using pre-contoured lordotic rods, both reduction of spondylolisthesis and posterior compression of the screw-rod construct were performed. In this process, we used reduction screws and "broke" the ProAxis bed from flexion to extension. The wound was then closed in a standard fashion.

Outcome Measures

Patient reported outcome (PRO) measures included the Oswestry Disability Index (ODI—normalized to 100%) and the Numeric Rating Scale (NRS-BP/10) for low back pain. PROs and serial radiographs were obtained preoperatively, and at approximately postoperative day 1, 6 weeks, 3 months, 6 months, 1 and 2-year routine follow-ups. Two independent reviewers blinded to patients' outcomes assessed radiographic images.

Sagittal segmental parameters included segmental lordosis (SL), disc angle (DA),²³ anterior disc height (ADH), posterior disc height (PDH), and percent spondylolisthesis. Cage position was determined by the center point ratio (CPR),²⁴ and cage subsidence was defined as migration greater than 2-mm (Supplemental Figure 1).²⁵ Sagittal spinopelvic parameters were overall lumbar lordosis (LL), PI-LL mismatch, sacral slope (SS), and pelvic tilt (PT). Change in radiographic alignment was calculated by subtracting the postoperative from the preoperative measurement. Based on the minimal detectable change (MDC),²⁶ surgeries were considered to be “lordosing” if postoperative induction of segmental or overall lordosis was $\geq +4^\circ$ and “kyphosing” if $\leq -4^\circ$.²⁶

Statistical Analysis

Descriptive data were analyzed via univariate analyses. In our series, missing radiographic data ($<5\%$) were imputed using observed radiographic measurements based on predictive mean matching.²⁷⁻³⁰ We used 5 imputed datasets and pooled results according to Rubin's rules.^{31,32} Pearson correlations were used to evaluate the association of preoperative radiographic measures with Δ SL or Δ LL. Variables that had a $P < .1$ were entered into multivariable linear regression models, with $P < .05$ used as the threshold for retention. The intraclass

correlation coefficient (ICC) was calculated for a subset of 10% of the radiographs to assess the inter-rater reliability. All statistical analyses were performed in R, version 4.1.4.

Results

A total of 73 patients were included in this study with a mean follow-up of 22.5 months (range 12-61 months). The male:female ratio was 40:32 (55/44%) and 44 (60%) patients had an ASA score ≤ 2 . The majority of patients underwent L4-5 level surgeries ($n = 57$, 68%). All patients experienced significant improvements in ODI ($29\% \pm 23\%$ improvement, $P < .001$) and NRS-BP (3.3 ± 3 point improvement, $P < .001$) at latest follow-up (Figure 1). One patient experienced a postoperative epidural hematoma that was evacuated and was subsequently discharged home in good condition. Eight (12%) patients underwent reoperation for pseudarthrosis ($n = 1$), adjacent segment disease ($n = 5$), or hardware failure ($n = 2$). There was no difference in pseudarthrosis rates requiring revision surgery between straight and articulating cages ($P = 1$). Cage subsidence was observed in 22 (30%) cases, two of which were grade 1 (25-50% loss of postoperative disc height).³³ Complete descriptive statistics and surgical details for the overall series are shown in Table 1. The ICC revealed “excellent” agreement in measuring radiographic parameters (all $>.90$).

Index-Level Segmental Parameters

Seventy (96%) patients were assessed at minimum 1-year follow-up, with longitudinal local radiographic parameters detailed in Table 2. Overall, SL increased from $6.34^\circ \pm 3.61^\circ$ preoperatively to $9.76^\circ \pm 4.39^\circ$ at latest follow-up ($\Delta 3.43^\circ \pm 4.37^\circ$ ($P < .001$; range: -8.35° to $+12.38^\circ$, Figure 2(A)). Thirty-eight (52%) patients experienced lordosing, 4 (5%)

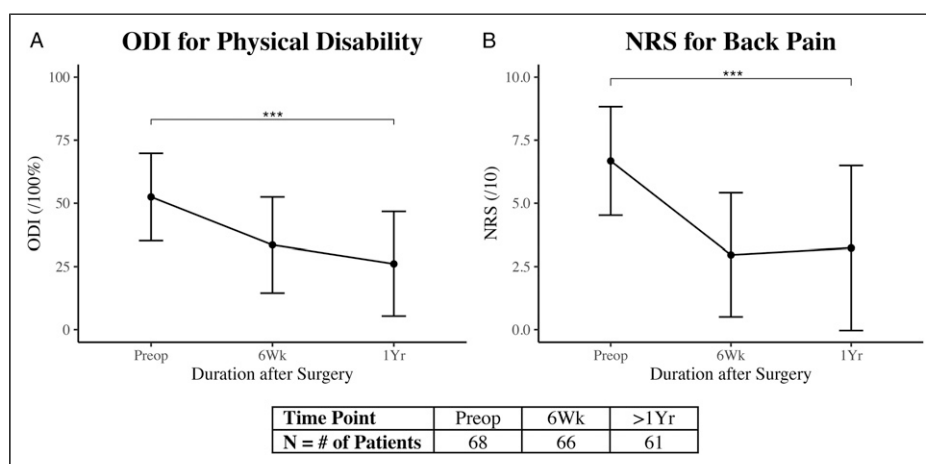


Figure 1. Longitudinal data describing patient-reported outcome (PRO) measures obtained preoperatively and at latest follow-up after MI-TLIF surgery. The smooth lines represent mean PRO scores with error bars representing SD in both directions. All MI-TLIF patients experienced significant improvements in ODI (A) and NRS-BP (B) at >1-year follow up compared to baseline status (*** $P < .001$). ODI: Oswestry Disability Index for physical disability (/100%); NRS: Numeric Rating Scale for low back pain (/10).

Table 1. Patient Demographics, clinical, and surgical Characteristics.

Characteristic	MI-TLIF
	N = 73
Age at surgery, years	64.5 ± 8.7
Preoperative BMI, kg/m ²	29.9 ± 4.9
Sex, M:F	40:32
ASA score, no.	
≤2	44 (60%)
>2	29 (40%)
Preoperative ODI _i /100%	52.8 ± 17.9%
Operative levels, no.	
L1-2	0
L2-3	7 (10%)
L3-4	8 (11%)
L4-5	57 (78%)
L5-S1	1 (1%)
Cage type	
Bullet	12 (16%)
Banana	61 (84%)
Est. Blood loss, mL	72 ± 57.1
Blood transfusions, mL	0
Op time, min	280.8 ± 79.3
Length of stay, hrs	39.6 ± 28.7
Disposition	
Home	65 (89%)
Rehab	8 (11%)
Complications	
Intraoperative	0
Postoperative	1 (1%)
Cage subsidence [†]	22 (30%)
Fusion status, no.	64 (88%)
Postoperative ODI (1-year)/100%	24 ± 20.5%
Change in ODI _i /100%	-29.1 ± 22.7%
Readmission, 30 d	0
Revision/Reoperation, no.	8 (11%)
Pseudarthrosis	1
ASD	5
Hardware failure	2
Follow-up duration, months	22.5 (range 12-61)

*ODI = Oswestry disability index.

†defined as migration greater than 2-mm; ASD: Adjacent segment disease.

kyphosing, and 31 (43%) neutral TLIFs (Supplemental Table 1). On bivariate analyses, preoperative SL ($r = -.41$, $P < .001$), ADH ($r = -.25$, $P = .03$), and cage position ($r = .46$, $P < .001$) were significantly correlated with Δ SL (Figure 2(B)–(D)). Level treated, cage type, and cage subsidence were not associated with Δ SL ($P > .05$). On multivariable regression analyses, preoperative SL (β [95% CI]: $-.45$ [-.59, -.32], $P = .001$) and cage position (β [95% CI]: 15.06 [11.11, 19.02], $P < .001$) remained as significant predictors (Table 3).

Overall Lumbar Lordosis and Pelvic Parameters

When assessing overall lumbar lordosis and pelvic parameters, sixty-nine (95%) patients were included at minimum 1-year follow-up. Mean baseline LL, PI-LL mismatch, SS, and PT were $56.44^\circ \pm 11.77^\circ$, $10.27^\circ \pm 8.43^\circ$, $38.6^\circ \pm 9.37^\circ$, and $22.35^\circ \pm 9.93^\circ$ respectively, and were not different at latest follow-up (Figure 3(A), Table 2, $P > .05$). When assessing change in LL, 20 (27%) patients experienced lordosing, 22 (30%) kyphosing, and 31 (43%) neutral TLIFs (Supplemental Table 1). On bivariate analyses, preoperative LL ($r = -.31$, $P = .008$), PI-LL mismatch ($r = .32$, $P = .005$), PT ($r = .30$, $P = .009$), and DA ($r = -.25$, $P = .03$), were significantly correlated with Δ LL (Figure 3(B)–(E)). Level treated, cage type, and cage subsidence were not associated with Δ LL ($P > .05$). However, on multivariable regression analyses, no variables were significantly associated with Δ LL (Table 4).

Stratification of Outcomes by Lordotic Group

When comparing lordosing, kyphosing, and preserving subgroups based on Δ SL, spinopelvic parameters (i.e., LL, PI-LL mismatch, sacral slope, and pelvic tilt) and clinical outcomes (i.e., ODI and NRS-BP), were not significantly different among groups (all $P > .05$, Table 5). However, with respect to index-level radiographic parameters, the lordosing group experienced significantly greater improvements in SL, disc angle, and anterior disc height, with more anterior cage placement (all $P < .001$, Table 5).

While multivariable regression results from the multiple imputed datasets are reported, as a sensitivity test, all analyses were also performed in the complete-case dataset and documented in Supplemental Tables 2 and 3.

Discussion

MI-TLIF is a useful technique to address degenerative lumbar etiologies; however, its ability to induce lordosis remains controversial, with several studies reporting MI-TLIF to be a kyphosis-inducing operation.^{14,34} Multiple practices have been developed to combat these deficiencies, from lordotic operative tables³⁵ to advancements in medical devices³⁶⁻³⁸ and surgical techniques.¹⁷

However, there is significant heterogeneity in studies investigating restoration of lordosis following MI-TLIF.³⁹ Inclusion of single-level and multi-segment procedures in the same study prevents accurate conclusions regarding SL and LL outcomes. Variation in interbody devices and surgical techniques further confound findings.³⁹ In addition, many studies lack long-term follow up, and therefore, fail to account for cage settling or subsidence.⁹ Given this evidence gap, we aimed to evaluate the impact of MI-TLIF on segmental and overall lumbar lordosis, with all other factors, including levels treated, surgical technique, and cage type, remaining constant.

Table 2. Summary of local and regional radiographic measurements.

	MI-TLIF			
	N = 73			
	Preop	Postop	Change	P-value
Index-level parameters				
Segmental lordosis, °	6.34° ± 3.61°	9.76° ± 4.39°	3.43° ± 4.37°	<.001
Disc angle, °	7.33° ± 3.54°	8.15° ± 4.2°	.79° ± 3.86°	.20
Anterior disc height, mm	10.88 ± 3.07 mm	12.44 ± 3.76 mm	1.52 ± 4.2 mm	.01
Posterior disc height, mm	8.16 ± 1.85 mm	6.55 ± 2.2 mm	-1.62 ± 2.65 mm	<.001
Percent spondylolisthesis, %	17.82 ± 7.84% mm	4.46 ± 5.52% mm	-13.41 ± 7.89% mm	<.001
Center point ratio	.62 ± .11 mm			
Spinopelvic parameters				
Overall lumbar lordosis, °	56.44° ± 11.77°	56.61° ± 11.7°	.17° ± 6.98°	.93
PI - LL mismatch, °	10.27° ± 8.43°	8.66° ± 7.17°	-1.62° ± 7.27°	.22
Sacral slope angle, °	38.6° ± 9.37°	39.38° ± 8.91°	.84° ± 7°	.61
Pelvic tilt, °	22.35° ± 9.93°	21.11° ± 7.59°	.21° ± 8.93°	.40

Predictors of Lordosis in MI-TLIF

Consistent with previous studies evaluating single-level MI-TLIF, we found preoperative spine habitus to be significantly associated with radiographic outcomes.^{16,40} In a cohort of 171 single-level MI-TLIF patients, Vaishnav et al⁴⁰ demonstrated that patients with low preoperative SL (<15°) experienced the greatest correction in SL regardless of cage type. Regarding regional alignment, Khalifeh et al¹⁶ reported in a cohort of 68 patients undergoing transfacet MI-TLIF that patients with hypolordotic spine types (LL <40°) experienced the greatest increases in SL and LL. Specifically, in our series, baseline SL predicted Δ SL at long-term follow-up, a finding that persisted on multivariable regression analysis. This finding may be attributable to the fact that hypolordotic spine types possess a higher propensity for radiographic improvement compared to hyperlordotic patients, who are at or near maximal lordosis.^{5,9}

In addition to patient-specific factors (e.g., radiographic habitus), interbody devices can also have significant implications on postoperative lordosis. Interbody device technology makes MI-TLIF possible, as narrowed working corridors prevent placement of large cages.^{36,38} In our study, we found anterior cage positioning to be significantly associated with Δ SL, which was the strongest relationship in multivariable analyses.^{1,41-43} Our series saw 63 (86%) devices placed anteriorly (CPR >.5), with a mean CPR of .62 ± .11. Such placement maximizes the anterior pivot effect of the cage, lengthening the anterior column (reflected by Δ ADH: +1.52 ± 4.2 mm, P < .001), reducing rod strain, and providing a stiffer construct.⁴³ This finding may also partly explain why our series experienced a modest, yet significant decrease in PDH (Δ -1.62 ± 2.65 mm, P < .001). However, this decrease in PDH was not associated with new-onset neurological deficits in our series, a finding that is further corroborated by steady improvements in ODI and NRS (Figure 1).

In addition to its effect on lordosis, cage placement onto the cortical load-bearing anterior hypophyseal ring has shown to reduce the risk of cage subsidence.⁴⁴ In the MI-TLIF literature, cage subsidence has shown to decrease disc height and lordosis, potentially preventing fusion and worsening outcomes.⁴⁵ A variety of risk factors of cage subsidence have been identified, ranging from low bone mineral density⁴⁶ to surgical technique,²⁵ with mixed evidence regarding the risk of cage subsidence in expandable vs static cages.^{36,37,47} At our institution, recognizing the risk of expandable cages due to an increased axial compression load at the cage-endplate interface,⁴⁴ we take care in ensuring anterior placement of our interbody device onto the cortical load-bearing fibrous anterior hypophyseal ring. In our series, we suggest that anterior cage positioning may have reduced the risk of cage subsidence, thereby limiting potential loss of postoperative lordosis. Ultimately, we found that the impact of cage subsidence at long-term follow-up was not substantial enough to have a major effect on Δ SL or Δ LL.

In comparison to Δ SL and consistent with existing literature, our patients did not experience significant changes in overall lumbar lordosis at latest follow-up (Δ LL: .17° ± 6.98°, Figure 3(A)).^{19,21} However, the neutral effects on overall lumbar lordosis were expected, as patients in our series underwent solely single-level surgery without osteotomies. These results suggest that adjacent unfused segments compensated for the modest changes in segmental lordosis to produce a stable overall alignment.^{48,49} Though many preoperative radiographic parameters correlated with Δ LL (Figure 3(B)–(E)), none persisted on multivariable analysis (Table 4). Finally, we found multivariable regression results to be identical between the multiple imputation analysis (Tables 3 and 4) and complete case analysis (Supplemental Tables 2 and 3), further demonstrating the durability of these findings.

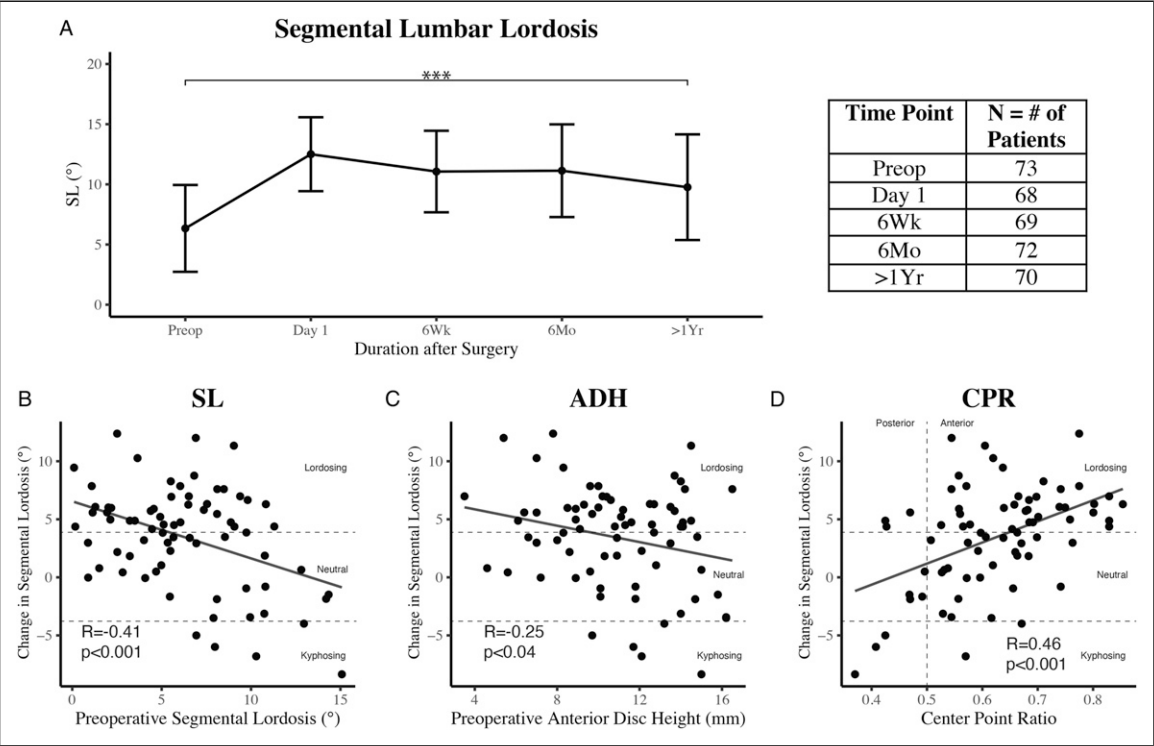


Figure 2. (A) Longitudinal data describing segmental lordosis obtained preoperatively and during routine postoperative clinic visits following MI-TLIF. Smooth lines represent the mean lordotic angle (°) with error bars representing SD in both directions. On average, MI-TLIF patients experienced significant improvements in segmental lordosis ($^{***}P < .001$) at >1-year follow up compared to baseline status. Preoperative segmental lordosis (B), anterior disc height (C), and center point ratio (D) were significantly correlated with change in segmental lordosis at last follow up, with ordinary least squares (OLS) regression lines shown. Horizontal dashed lines delineate lordosing, neutral, and kyphosing MI-TLIF according to the minimal detectable change (MDC) associated with Cobb's lumbar lordosis (4°). The vertical dashed line (D) refers to a center point ratio of .5, indicating midline cage placement.

Table 3. Multivariable regression analysis of predictors of change in segmental lordosis.

Model variable	Beta coefficient (95% CI)	P-value
Preoperative ADH	.01 (-.18 to .19)	.976
Preoperative PI-LL mismatch	-.1 (-.15 to -.04)	.073
Preoperative SL	-.45 (-.59 to -.32)	.001
Preoperative spondylolisthesis	.05 (-.01 to .11)	.397
Center point ratio	15.06 (11.11 to 19.02)	<.001

Important to note, lordosis in the lumbar spine is not homogenously distributed.^{50,51} In order to account for this potential confounder of postoperative lordosis, a subgroup analysis was performed comparing ΔSL and ΔLL between levels treated. Specifically, surgeries were binned into those undergoing L4-5 (n = 57, 78%) or L5-S1 (n = 1, 1%) vs L2-3 (n = 7, 10%) or L3-4 (n = 8, 11%). For ΔSL, the L4-5 or L5-S1 group improved by 3.41° ± 4.43° whereas the L2-3 or L3-4 group improved by 3.19° ± 4.5° (P = .87). For ΔLL, the L4-5 or L5-S1 group improved by .63° ± 7.08° whereas the L2-3 or L3-4 group decreased by -2.08° ± 5.98° (P = .16). In addition,

the level treated was not a significant predictor of ΔSL or ΔLL on multivariable regression. Therefore, while lumbar lordosis is not evenly distributed throughout the lumbar spine, the level treated in our study did not significantly impact our results.

Findings in Context

Though existing studies have assessed the effect of MI-TLIF on sagittal alignment,^{9,19,39,40,52} heterogenous patient populations limit robust assessments of radiographic predictors of segmental and global lordosis. Specifically, inclusion of multi-level surgery, variation in facetectomy technique, and use of differing cage technology may confound analyses. Consistent with previous studies,^{40,43} we reinforce the importance of preoperative patient selection and operative technique on sagittal alignment following MI-TLIF. Our long-term follow-up (mean: 22.5 months) and multivariable analyses controlling for multiple confounders, including the effects of cage subsidence, further demonstrate the durability of our findings.

Similar to previous reports, the majority of patients in our series experienced lordosing MI-TLIFs when defined using the MDC (4°) of Cobb's lumbar lordosis²⁶ (n = 38, 52%) or as

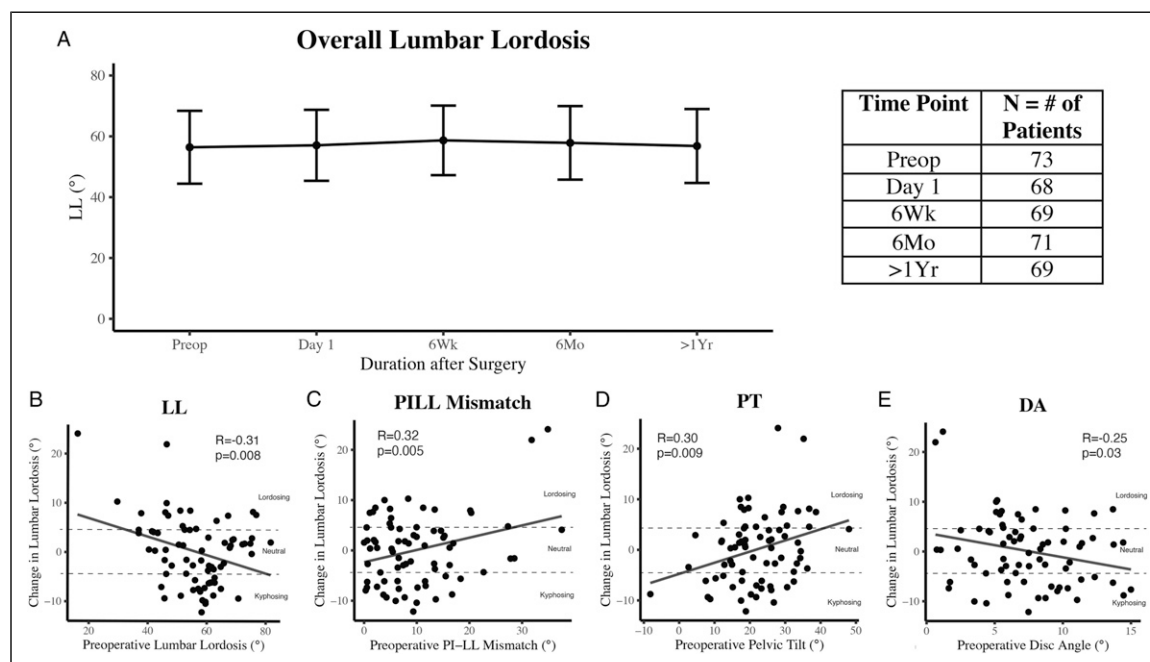


Figure 3. (A) Longitudinal data describing overall lumbar lordosis obtained preoperatively and during routine postoperative clinic visits following MI-TLIF. Smooth lines represent the mean lordotic angle (°) with error bars representing SD in both directions. Overall lumbar lordosis remained stable at >1-year follow. Preoperative overall lumbar lordosis (B), PI-LL mismatch (C), pelvic tilt (D), and disc angle (E) were significantly correlated with change in overall lumbar lordosis at latest follow up, with ordinary least squares (OLS) regression lines shown. Horizontal dashed lines delineate lordosing, neutral, and kyphosing MI-TLIF according to the minimal detectable change (MDC) associated with Cobb's lumbar lordosis (4°). PI-LL: Pelvic incidence — lumbar lordosis.

Table 4. Multivariable regression analysis of predictors of change in overall lumbar lordosis.

Model variable	Beta coefficient (95% CI)	P-value
Preoperative lumbar lordosis	-.09 (-.17 to -.01)	.254
Preoperative PI-LL mismatch	.13 (.03 to .23)	.199
Preoperative PT	.14 (.05 to .23)	.113
Preoperative DA	-.28 (-.53 to -.03)	.266

$\Delta SL > 0^\circ$ ($n = 54$, 74%) as described in prior studies.⁹ We suggest that the increases in SL seen in our case may be attributed to the combined effects of expandable cage technology, cage positioning, use of an advanced adjustable operating bed, and maintenance of the posterior tension band.

As opposed to open TLIF, the posterior ligamentous complex⁵³ remains intact in MI-TLIF. Maintenance of these structures limits expansion of the posterior vertebra, which can be leveraged to maximize restoration of segmental lordosis. Under these circumstances (i.e., mobile anterior disc and relatively fixed posterior disc), cage positioning becomes paramount. Specifically, anterior placement of the interbody device can maximize the construct's "wedge" effect, promoting segmental lordosis (Figure 4(A)). Conversely, if the cage is placed too posteriorly, the superior vertebral body may hinge over the device, potentially kyphosing the local segment

(Figure 4(B)). Indeed, we found cage positioning to be the strongest predictor of ΔSL , with every .1 increase in CPR predicting a 1.5° increase in SL (Table 3).

This phenomenon may be further augmented through the use of expandable interbody devices, which are increasingly utilized during MI-TLIF to address technical limitations of an minimally-invasive approach.³⁸ In our series, 61 (84%) of the expandable interbody devices were articulating "banana" cages and 12 (16%) were straight "bullet" devices. Developed more recently to combat the alleged kyphosing nature of TLIFs, articulating "banana" cages theoretically provide greater index-level lordosis through their improved ability to articulate along the anterior apophyseal ring.⁴⁹ As compared to a recent study by Toop et al,⁴⁹ our series found no difference between articulating ($\Delta SL: 3.23^\circ \pm 4.39^\circ$) and straight cages ($\Delta SL: 3.18^\circ \pm 4.36^\circ$) ($P = .97$). This may be due to our unequal distribution of cage types, smaller sample size, or other patient-specific factors, and therefore, should be further evaluated in future studies.

Though expandable cages may theoretically provide larger increases in lordosis than non-expandable cages, complications such as cage subsidence and cage migration can nullify these potential advantages.³⁷ Although our study was unable to compare static and expandable cages, there is a strong body of literature that suggests that static cages can likely achieve similar lordotic outcomes in single-level MI-TLIF. In

Table 5. Summary of clinical and radiographic outcomes stratified by Δ SL group.

	Δ SL group ^a			
	Lordosing	Kyphosing	Preserving	
	N = 38	N = 4	N = 31	P-value ^b
Radiographic measurements				
Index-level parameters				
Segmental lordosis, °	6.58 ± 2.22	-6.54 ± 1.42	.63 ± 2.44	<.001
Disc angle, °	2.78 ± 3.67	-3.9 ± 1.3	-.39 ± 3.16	<.001
Anterior disc height, mm	3.47 ± 2.96	-3.87 ± 1.75	-.14 ± 4.11	<.001
Posterior disc height, mm	-1.16 ± 2.55	-2.93 ± 1.89	-2.07 ± 2.56	.216
Percent spondylolisthesis, %	-12.72 ± 6.61	-7.34 ± 10.68	-13.73 ± 7.77	.276
Center point ratio	.66 ± 0.1	.44 ± .09	.6 ± .08	<.001
Spinopelvic parameters				
Overall lumbar lordosis, °	.76 ± 5.02	-6.81 ± 2.25	.19 ± 8.72	.115
PI - LL mismatch, °	.05 ± 6.15	-1.69 ± 5.72	-3.88 ± 7.71	.073
Sacral slope angle, °	1.31 ± 5.58	-2.44 ± 4.44	-.41 ± 7.45	.389
Pelvic tilt, °	-.68 ± 6.32	2.9 ± 6.45	-.83 ± 9	.719
Clinical outcomes				
Oswestry disability index	-25.15 ± 21.28	-48.67 ± 30.55	-26.48 ± 21.74	.221
Numeric rating score, back pain	-3.12 ± 2.93	-3.41 ± 3.1	-3.86 ± 3.3	.514

^aBased on the minimal detectable change (MDC): Lordosing = Δ SL $\geq +4^\circ$ and kyphosing = Δ SL $\leq -4^\circ$.

^bOne-way analysis of variance (ANOVA); SL: segmental lordosis; ADH: Anterior disc height; PDH: Posterior disc height; FH: foraminal height; Spondy: spondylolisthesis; LL: overall lumbar lordosis; PI-LL: Pelvic incidence lumbar lordosis; SS: sacral slope; PT: pelvic tilt.

comparative studies assessing lordotic outcomes between static and expandable cages, the evidence remains mixed.^{21,38,54} In a meta-analysis comparing static and expandable MI-TLIF patients, Ali Alvi et al³⁶ demonstrated the superior ability of expandable cages to promote segmental lordosis compared to static cages, with neutral effects on overall lumbar lordosis. Taken together, the literature suggests that both static and expandable cages are capable of providing similar restoration of lordosis after single-level MI-TLIF. The variation in results in existing literature implies that interbody device type alone is not the primary determinant factor of lordotic outcomes, but rather a combination of operative technique, interbody devices, and surgical adjuncts.

Furthermore, all patients in our series utilized an open-frame hinged surgical table. In our institution, we utilize a flexed position to support decompression, instrumentation, and interbody device placement, followed by an extended position to fix the patient in a lordotic alignment during rod insertion.^{21,35} Although their true efficacy has not been established, these adjustable operative tables may have further contributed to the gains in segmental lordosis seen in our series.

Surgical technique has also been associated with corrections in lordosis.^{9,17} Specifically, though the evidence is mixed, bilateral facetectomies have been suggested to promote greater correction in lordosis.^{1,9,17,22} Biomechanically, bilateral facetectomies theoretically allows for greater compression across the instrumented vertebra to promote lordosis, with

support from recent cadaveric studies.⁵⁵ However, in a study of 57 patients undergoing open TLIF with either unilateral or bilateral facetectomy, Tye et al⁵⁶ found no difference in SL correction at 1-year follow-up. In a more recent study in a cohort of 40 MI-TLIF patients, Archer et al²² also did not find significant differences in SL when comparing unilateral and bilateral facetectomies. The conflicting evidence may suggest inconsistencies in surgeon technique, including the size and extent of the facetectomy, as well as confounding from other variables (e.g., cage type, operative bed, cage positioning, extent of posterior compression). In addition, in MI-TLIF, maintenance of the posterior ligamentous complex may interfere with posterior compression of the screw-rod construct.

Though bilateral facetectomies may have increased our lordotic potential, our study only included unilateral facetectomies with contralateral facet release, which allowed for a homogenous series of patients. Furthermore, our results suggest that advanced interbody device technology (i.e., expandable “banana” cages), anterior cage placement, ancillary surgical adjuncts (e.g., modulating ProAxis table), and careful patient selection are still contributors to improvements in lordosis, independent of facetectomy technique. Our long-term follow up (mean: 22.5 months) coupled with our low incidence of reoperations (11%) further demonstrate the stability of our results.

Our findings emphasize that predictors of alignment correction are multifactorial and cannot be predicted solely based on the type of interbody fusion procedure performed.^{5,49}

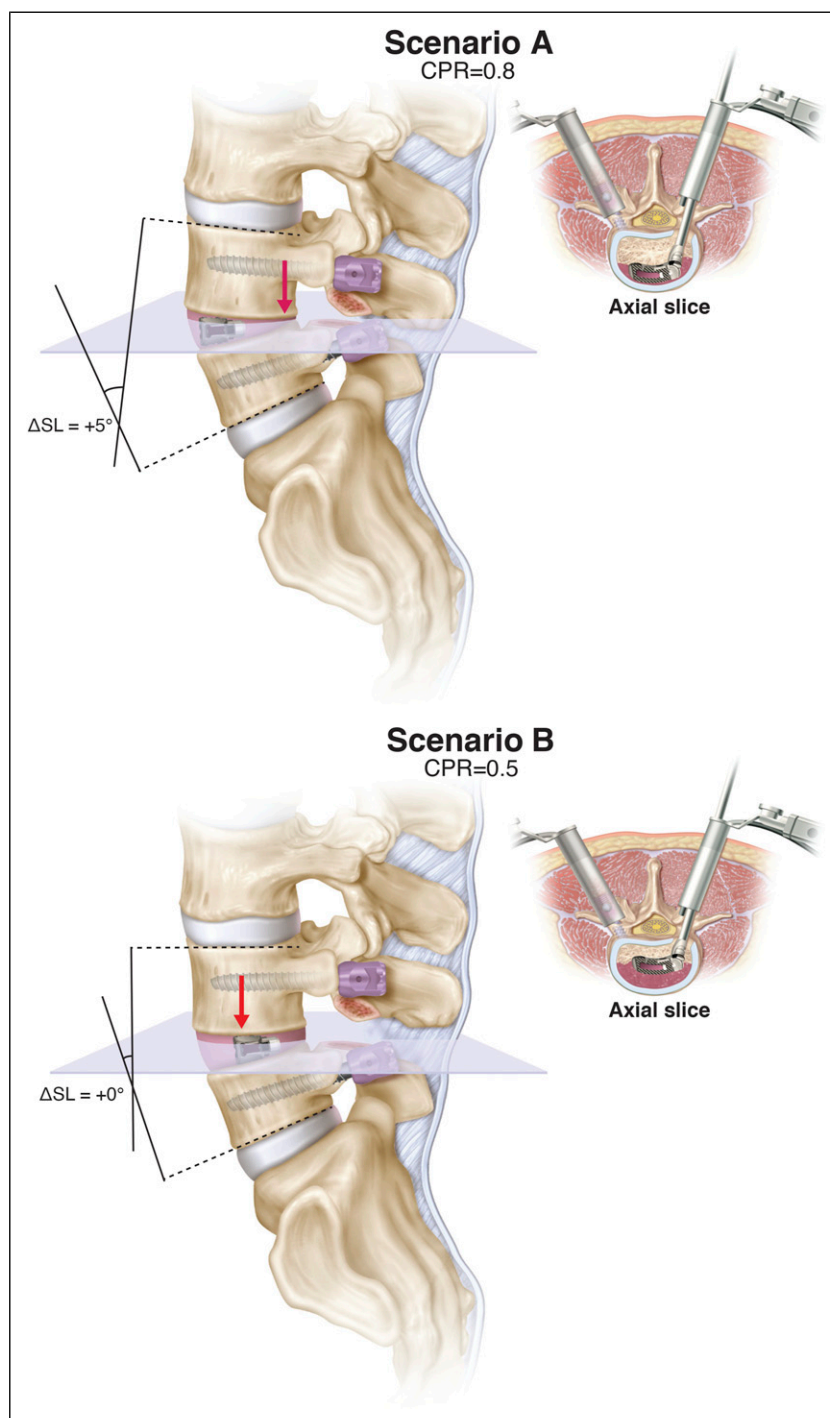


Figure 4. Illustration demonstrating the effect of expandable cage positioning on segmental lordosis in single-level MI-TLIF treated with unilateral facetectomy and expandable interbody devices. **Scenario (A)** Neutral MI-TLIF. The CPR is .5, indicated midline placement (**Axial slice**), leading to no change in segmental lordosis ($\Delta SL = 0^\circ$). **Scenario (B)** Lordosing MI-TLIF. The CPR is .8, indicating anterior placement (**Axial slice**), maximizing the anterior pivot (**red arrow**), promoting segmental lordosis ($\Delta SL +5^\circ$).

However, they are meaningful as they may enable surgeons to have greater accuracy in their preoperative plan. In a narrative review of various types of minimally invasive interbody procedures, Uribe et al⁵ makes the distinction between alignment ‘preservation’ vs ‘restoration’ following interbody fusion.

Taken together, our results suggest that single-level MI-TLIF, *under certain situations*, is able to *restore* segmental lordosis. More specifically, it can maintain alignment without exacerbating underlying kyphosis. Therefore, if a surgeon aims on treating single-level degenerative lumbar disease through MI-

TLIF, careful assessment of the patient's preoperative radiographic habitus and attention to cage placement intraoperatively may maximize the ability to adequately restore SL.

In addition, our results suggest that single-level MI-TLIF, *under our study conditions*, has a neutral effect on overall lumbar lordosis and is generally sufficient to *preserve* global lordosis. As reflected through our results, in the setting of single-level surgery, global sagittal alignment (e.g., PI-LL mismatch) and clinical outcomes were not significantly different among lordosing, kyphosing, and preserving subgroups defined using Δ SL (Table 5). As expected, changes in certain index-level radiographic parameters (e.g., SL, DA, ADH) were significantly greater in lordosing patients ($P < .001$). This is likely in part due to significantly greater CPR values in lordosing patients ($P < .001$) indicating more anterior cage placement, promoting a "wedge" effect. Important to note, however, the gains in lordosis seen in our cohort were still modest. Specifically, a mean improvement of 4° may not translate into meaningful sagittal correction and lordotic gains should be interpreted in the context of the patient's overall alignment and needs for lordosis. Consequently, if *restoration* of overall lumbar lordosis is the goal of surgery, surgeons may need to perform a different interbody fusion approach, such as an anterior lumbar interbody fusion (ALIF),¹⁴ or consider use of alignment-correcting osteotomy techniques.

Limitations

Limitations of this study include its single-center design and retrospective nature. In addition, given that all patients underwent the same surgery (i.e., all single-level MI-TLIF performed on an open-frame hinged surgical table with unilateral facetectomies and a contralateral facet release with expandable cages), we were unable to assess the individual contribution of operative technique (i.e., modular operative table, cage placement, facetectomy type, instrumentation technique) or interbody device types (e.g., expandable vs static cages). Future studies comparing these domains while keeping other variables constant are critical to assessing the contributory effect of factors influencing lordosis.

Furthermore, our study includes two types of expandable interbody devices. One subtype, our straight "bullet" cage, does not allow for packing of bone graft after expansion, and therefore, has a theoretical increased risk for pseudarthrosis because pre-placed bone graft is less tightly packed. However, given that our study cohort only had one case of pseudarthrosis requiring revision surgery, we were not able to compare arthrodesis success between these cage types. Moreover, patients in our cohort experienced significant reductions in spondylolisthesis, similar to previous studies assessing radiographic outcomes following single-level MI-TLIF.^{57,58} Although our study focused on lordotic outcomes

following MI-TLIF, future studies should examine predictors of other radiographic outcomes, such as reduction of spondylolisthesis. Last, though we included two independent reviewers, some of our findings are within the measurement error for Cobb's lordosis²⁶ and may have limited clinical translations.

Conclusions

Given conflicting reports describing sagittal correction following MI-TLIF, we examine a homogenous, consecutive series of single-level MI-TLIF patients undergoing unilateral facetectomies and a contralateral facet release with expandable cages. In our series, the majority of patients experienced restoration of segmental lordosis (52%, $n = 38$), with neutral effects on overall alignment. At latest follow-up, preoperative segmental lordosis and cage position were significant predictors of Δ SL, which remained significant when including potential confounders on multivariable regression. Our results suggest that in order to maximize lordotic potential in single-level MI-TLIF approaches, surgeons should carefully select patients based on preoperative spine habitus and maximize anterior cage placement intraoperatively.

Appendix

Abbreviations

ADH	Anterior disc height
ASA	American Society of Anesthesiologists
BMI	Body mass index
ICC	Intraclass correlation coefficient
LL	Lumbar lordosis
MDC	Minimal detectable change
MI	Minimally-invasive
NRS-BP	Numeric Rating Scale for low back pain
ODI	Oswestry Disability Index
PDH	Posterior disc height
PI	Pelvic incidence
PI-LL	Mismatch of PI and LL
PLIF	Posterior lumbar interbody fusion
PRO	Patient reported outcomes
PT	Pelvic tilt
SL	Segmental lordosis
SS	Sacral slope
STROBE	Strengthening the Reporting of Observational Studies in Epidemiology
TLIF	Transforaminal lumbar interbody fusion
VAS	Visual Analog Scale

Acknowledgements

The authors would like to acknowledge Dr Yikyung Park for her biostatistical support.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iDs

Justin K. Zhang  <https://orcid.org/0000-0002-8170-4733>
 Jacob K. Greenberg  <https://orcid.org/0000-0003-2675-5658>
 Kathleen S. Botterbush  <https://orcid.org/0000-0003-2721-0684>
 Brenton H. Pennicooke  <https://orcid.org/0000-0002-4304-9141>

Supplemental Material

Supplemental material for this article is available online.

References

- Jagannathan J, Sansur CA, Oskouian RJ, Fu KM, Shaffrey CI. Radiographic restoration of lumbar alignment after transforaminal lumbar interbody fusion. *Neurosurgery*. 2009;64(5):955-963. discussion 963-4.
- Rothenfluh DA, Mueller DA, Rothenfluh E, Min K. Pelvic incidence-lumbar lordosis mismatch predisposes to adjacent segment disease after lumbar spinal fusion. *Eur Spine J*. 2015;24(6):1251-1258.
- Alvi MA, Kurian SJ, Wahood W, Goyal A, Elder BD, Bydon M. Assessing the difference in clinical and Radiologic outcomes between expandable cage and Nonexpandable cage among patients undergoing minimally invasive transforaminal interbody fusion: a systematic review and meta-analysis. *World Neurosurg*. 2019;127:596-606. e1.
- Liang Y, Shi W, Jiang C, et al. Clinical outcomes and sagittal alignment of single-level unilateral instrumented transforaminal lumbar interbody fusion with a 4 to 5-year follow-up. *Eur Spine J*. 2015;24(11):2560-2566.
- 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*. 2016;41(Suppl 8):S50-S58.
- Foley KT, Lefkowitz MA. Advances in minimally invasive spine surgery. *Clin Neurosurg*. 2002;49:499-517.
- Rothrock RJ, McNeill IT, Yaeger K, Oermann EK, Cho SK, Caridi JM. Lumbar lordosis correction with interbody fusion: Systematic literature review and analysis. *World Neurosurgery*. 2018;118:21-31.
- Phani Kiran S, Sudhir G. Minimally invasive transforaminal lumbar interbody fusion - a narrative review on the present status. *J Clin Orthop Trauma*. 2021;22:101592.
- Liu J, Duan P, Mummaneni PV, et al. Does transforaminal lumbar interbody fusion induce lordosis or kyphosis? Radiographic evaluation with a minimum 2-year follow-up. *J Neurosurg Spine*. 2021;2021:1-8.
- Goldstein CL, Macwan K, Sundararajan K, Rampersaud YR. Perioperative outcomes and adverse events of minimally invasive versus open posterior lumbar fusion: meta-analysis and systematic review. *J Neurosurg Spine*. 2016;24(3):416-427.
- Hammad A, Wirries A, Ardeschiri A, Nikiforov O, Geiger F. Open versus minimally invasive TLIF: literature review and meta-analysis. *J Orthop Surg Res*. 2019;14(1):229.
- Qin R, Liu B, Zhou P, et al. Minimally invasive versus traditional open transforaminal lumbar interbody fusion for the treatment of single-level spondylolisthesis grades 1 and 2: a systematic review and meta-analysis. *World Neurosurg*. 2019;122:180-189.
- Miller LE, Bhattacharyya S, Pracyk J. Minimally invasive versus open transforaminal lumbar interbody fusion for single-level degenerative disease: a systematic review and meta-analysis of Randomized controlled Trials. *World Neurosurg*. 2020;133:358-365. e4.
- Hsieh PC, Koski TR, O'Shaughnessy BA, et al. Anterior lumbar interbody fusion in comparison with transforaminal lumbar interbody fusion: implications for the restoration of foraminal height, local disc angle, lumbar lordosis, and sagittal balance. *J Neurosurg Spine*. 2007;7(4):379-386.
- Agha RA, Sohrai C, Mathew G, Franchi T, Kerwan A, O'Neill N. The PROCESS 2020 guideline: updating consensus preferred reporting of CasE Series in surgery (PROCESS) guidelines. *Int J Surg*. 2020;84:231-235.
- Khalifeh JM, Dibble CF, Stecher P, Dorward I, Hawasli AH, Ray WZ. Transfacet minimally invasive transforaminal lumbar interbody fusion with an expandable interbody device—part II: consecutive case series. *Operative Neurosurgery*. 2020;19(5):518-529.
- Le H, Anderson R, Phan E, et al. Clinical and radiographic comparison between open versus minimally invasive transforaminal lumbar interbody fusion with bilateral facetectomies. *Global Spine J*. 2021;11(6):903-910.
- Lv Y, Chen J, Chen J, et al. Three-year postoperative outcomes between MIS and conventional TLIF in 1-segment lumbar disc herniation. *Minim Invasive Ther Allied Technol*. 2017;26(3):168-177.
- McMordie JH, Schmidt KP, Gard AP, Gillis CC. Clinical and short-term radiographic outcomes of minimally invasive transforaminal lumbar interbody fusion with expandable lordotic devices. *Neurosurgery*. 2020;86(2):E147-E155.
- Wong AP, Smith ZA, Stadler JA 3rd, et al. Minimally invasive transforaminal lumbar interbody fusion (MI-TLIF): surgical technique, long-term 4-year prospective outcomes, and complications compared with an open TLIF cohort. *Neurosurg Clin N Am*. 2014;25(2):279-304.
- 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.

22. Archer J, Flint K, Mendenhall S, Mobasser J-P. Unilateral versus bilateral facetectomy and its effect on segmental lordosis and disc height in MIS TLIF. *Journal of Spine Research and Surgery*. 2020;2:30-36.
23. Been E, Li L, Hunter DJ, Kalichman L. Geometry of the vertebral bodies and the intervertebral discs in lumbar segments adjacent to spondylolysis and spondylolisthesis: pilot study. *Eur Spine J*. 2011;20(7):1159-1165.
24. Landham PR, Don AS, Robertson PA. Do position and size matter? An analysis of cage and placement variables for optimum lordosis in PLIF reconstruction. *Eur Spine J*. 2017;26(11):2843-2850.
25. Yao YC, Chou PH, Lin HH, Wang ST, Liu CL, Chang MC. Risk factors of cage subsidence in patients received minimally invasive transforaminal lumbar interbody fusion. *Spine*. 2020;45(19):E1279-E1285.
26. Hicks GE, George SZ, Nevitt MA, Cauley JA, Vogt MT. Measurement of lumbar lordosis: inter-rater reliability, minimum detectable change and longitudinal variation. *J Spinal Disord Tech*. 2006;19(7):501-506.
27. Steyerberg EW, van Veen M. Imputation is beneficial for handling missing data in predictive models. *J Clin Epidemiol*. 2007;60(9):979.
28. van der Heijden GJ, Donders AR, Stijnen T, Moons KG. Imputation of missing values is superior to complete case analysis and the missing-indicator method in multivariable diagnostic research: a clinical example. *J Clin Epidemiol*. 2006;59(10):1102-1109.
29. van Leeuwen N, Lingsma HF, Perel P, et al. Prognostic value of major extracranial injury in traumatic brain injury: an individual patient data meta-analysis in 39,274 patients. *Neurosurgery*. 2012;70(4):811-818. discussion 818.
30. Zhang Z. Missing data imputation: focusing on single imputation. *Ann Transl Med*. 2016;4(1):9.
31. Wang KY, Vankov ER, Lin DDM. Predictors of clinical outcome in pediatric oligodendroglioma: meta-analysis of individual patient data and multiple imputation. *J Neurosurg Pediatr*. 2018;21(2):153-163.
32. van Ginkel JR, Linting M, Rippe RCA, van der Voort A. Rebutting existing Misconceptions about multiple imputation as a method for handling missing data. *J Pers Assess*. 2020;102(3):297-308.
33. 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.
34. Dorward IG, Lenke LG, Bridwell KH, et al. Transforaminal versus anterior lumbar interbody fusion in long deformity constructs: a matched cohort analysis. *Spine (Phila Pa 1976)*. 2013;38(12):E755-E762.
35. Sebastian AS, Ahmed A, Vernon B, et al. Effect of an adjustable hinged operating table on lumbar lordosis during lumbar surgery. *Spine (Phila Pa 1976)*. 2018;43(4):302-306.
36. Alvi MA, Kurian SJ, Wahood W, Goyal A, Elder BD, Bydon M. Assessing the difference in clinical and radiologic outcomes between expandable cage and nonexpandable cage among patients undergoing minimally invasive transforaminal interbody fusion: a systematic review and meta-analysis. *World Neurosurgery*. 2019;127:596-606. e1.
37. Armocida D, Pesce A, Cimatti M, Proietti L, Santoro A, Frati A. Minimally invasive transforaminal lumbar interbody fusion using expandable cages: increased risk of late postoperative subsidence without a real improvement of Perioperative outcomes: a clinical Monocentric study. *World Neurosurg*. 2021;156:e57-e63.
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.
39. 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.
40. Vaishnav AS, Saville P, McAnany S, et al. Retrospective review of Immediate restoration of lordosis in single-level minimally invasive transforaminal lumbar interbody fusion: a comparison of static and expandable interbody cages. *Oper Neurosurg (Hagerstown)*. 2020;18(5):518-523.
41. Kepler CK, Huang RC, Sharma AK, et al. Factors influencing segmental lumbar lordosis after lateral transpsoas interbody fusion. *Orthop Surg*. 2012;4(2):71-75.
42. Kwon BK, Berta S, Daffner SD, et al. Radiographic analysis of transforaminal lumbar interbody fusion for the treatment of adult isthmic spondylolisthesis. *J Spinal Disord Tech*. 2003;16(5):469-476.
43. Polly DW, Klemme WR, Cunningham BW, Burnette JB, Haggerty CJ, Oda I. The biomechanical significance of anterior column support in a simulated single-level spinal fusion. *Journal of spinal disorders*. 2000;13(1):58-62.
44. Yson SC, Santos ERG, Sembrano JN, Polly DW. Segmental lumbar sagittal correction after bilateral transforaminal lumbar interbody fusion: clinical article. *J Neurosurg: Spine SPI*. 2012;17(1):37-42.
45. Fukuta S, Miyamoto K, Hosoe H, Shimizu K. Kidney-type intervertebral spacers should be located anteriorly in cantilever transforaminal lumbar interbody fusion: analyses of risk factors for spacer subsidence for a minimum of 2 years. *J Spinal Disord Tech*. 2011;24(3):189-195.
46. Oh KW, Lee JH, Lee JH, Lee DY, Shim HJ. The correlation between cage subsidence, bone mineral density, and clinical results in posterior lumbar interbody fusion. *Clin Spine Surg*. 2017;30(6):E683-E689.
47. Calvachi-Prieto P, McAvoy MB, Cerecedo-Lopez CD, et al. Expandable versus static cages in minimally invasive lumbar interbody fusion: a systematic review and meta-analysis. *World Neurosurgery*. 2021;151:e607-e614.
48. Schwab JS, Diangelo DJ, Foley KT. Motion compensation associated with single-level cervical fusion: where does the lost motion go? *Spine (Phila Pa 1976)*. 2006;31(21):2439-2448.
49. Toop N, Viljoen S, Baum J, et al. Radiographic and clinical outcomes in one- and two-level transforaminal lumbar interbody

- fusions: a comparison of bullet versus banana cages. *J Neurosurg Spine*. 2021;2021:1-10.
50. Been E, Barash A, Marom A, Kramer PA. Vertebral bodies or discs: which contributes more to human-like lumbar lordosis? *Clin Orthop Relat Res*. 2010;468(7):1822-1829.
 51. Pesenti S, Lafage R, Stein D, et al. The amount of proximal lumbar lordosis is related to pelvic incidence. *Clin Orthop Relat Res*. 2018;476(8):1603-1611.
 52. 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.
 53. Vaccaro AR, Lee JY, Schweitzer KM Jr., et al. Assessment of injury to the posterior ligamentous complex in thoracolumbar spine trauma. *Spine J*. 2006;6(5):524-528.
 54. Vaishnav AS, Saville P, McAnany S, et al. Retrospective review of Immediate restoration of lordosis in single-level minimally invasive transforaminal lumbar interbody fusion: a comparison of static and expandable interbody cages. *Operative Neurosurgery*. 2020;18(5):518-523.
 55. Snyder LA, Lehrman JN, Menon RK, Godzik J, Newcomb A, Kelly BP. Biomechanical implications of unilateral facetectomy, unilateral facetectomy plus partial contralateral facetectomy, and complete bilateral facetectomy in minimally invasive transforaminal interbody fusion. *J Neurosurg Spine*. 2019;31(3):447-452.
 56. Tye EY, Alentado VJ, Mroz TE, Orr RD, Steinmetz MP. Comparison of clinical and radiographic outcomes in patients receiving single-level transforaminal lumbar interbody fusion with removal of unilateral or bilateral facet joints. *Spine (Phila Pa 1976)*. 2016;41(17):E1039-E1045.
 57. Park P, Foley KT. Minimally invasive transforaminal lumbar interbody fusion with reduction of spondylolisthesis: technique and outcomes after a minimum of 2 years' follow-up. *Neurosurgical Focus FOC*. 2008;25(2):E16.
 58. Dibble CF, Zhang JK, Greenberg JK, et al. Comparison of local and regional radiographic outcomes in minimally invasive and open TLIF: a propensity score-matched cohort. *J Neurosurg Spine*. 2022;11:1-11.