Asian Spine Journal
Clinical Study
Asian Spine J 2023;17(4):666-675 • https://doi.org/10.31616/asj.2022.0316

A Comparison of Radiographic Alignment between Bilateral and Unilateral Interbody Cages in Patients Undergoing Transforaminal Lumbar Interbody Fusion

Mark James Lambrechts, Jeremy Heard, Nicholas D'Antonio, John Bodnar, Gregory Schneider, Evan Bloom, Jose Canseco, Barrett Woods, Ian David Kaye, Mark Kurd, Jeffrey Rihn, Alan Hilibrand, Gregory Schroeder, Alexander Vaccaro, Christopher Kepler

Department of Orthopaedic Surgery, Rothman Orthopaedic Institute, Thomas Jefferson University Hospital, Philadelphia, PA, USA

Study Design: Retrospective cohort study.

Purpose: To compare radiographic outcomes between unilateral and bilateral cage placement in transforaminal lumbar interbody fusions (TLIF) and to determine if the rate of fusion at the 1-year postoperative point was different in patients who received bilateral versus unilateral cages.

Overview of Literature: There is no clear evidence to dictate whether bilateral or unilateral cages promote superior radiographic or surgical outcomes in TLIF.

Methods: Patients >18 years old who underwent primary one- or two-level TLIFs at our institution were identified and propensity-matched in a 3:1 fashion (unilateral:bilateral). Patient demographics, surgical characteristics, and radiographic outcomes, including vertebral endplate obliquity, segmental lordosis, subsidence, and fusion status, were compared between groups.

Results: Of the 184 patients included, 46 received bilateral cages. Bilateral cage placement was associated with greater subsidence (1.06±1.25 mm vs. 0.59±1.16 mm, p=0.028) and enhanced restoration of segmental lordosis (5.74°±14.1° vs. –1.57°±10.9°, p=0.002) at the 1-year postoperative point, while unilateral cage placement was associated with an increased correction of endplate obliquity (–2.02°±4.42° vs. 0.24°±2.81°, p<0.001). Bilateral cage placement was significantly associated with radiographic fusion on bivariate analysis (89.1% vs. 70.3%, p=0.018) and significantly predicted radiographic fusion on multivariable regression analysis (estimate, 1.35; odds ratio, 3.87; 95% confidence interval, 1.51–12.05; p=0.010).

Conclusions: Bilateral interbody cage placement in TLIF procedures was associated with restoration of lumbar lordosis and increased fusion rates. However, endplate obliquity correction was significantly greater for patients who received a unilateral cage.

Keywords: Spinal stenosis; Lordosis; Spondylolisthesis; Spinal fusion; Transforaminal lumbar interbody fusion

Received Aug 14, 2022; Revised Sep 17, 2022; Accepted Oct 17, 2022

Corresponding author: Mark James Lambrechts
Department of Orthopaedic Surgery, Rothman Orthopaedic Institute, Thomas Jefferson University, 925 Chestnut St, 5th Floor Philadelphia, PA 19107, USA
Tel: +1-215-955-6060, Fax: +1-215-503-5651, E-mail: mark.lambrechts@rothmanortho.com

Asian Spine Journal • pISSN 1976-1902 eISSN 1976-7846 • www.asianspinejournal.org

Introduction

Lumbar interbody fusions have become common for treating radiculopathy and neurogenic claudication caused by spondylolisthesis and/or spinal stenosis [1]. The placement of an interbody cage allows for indirect neural element decompression via ligamentotaxis while also optimizing lumbar lordosis and endplate obliquity correction [2]. In addition to providing indirect neuroforaminal decompression and sagittal balance restoration, interbody fusions increase the likelihood of arthrodesis through anterior column stabilization [3]. Although transforaminal lumbar interbody fusion (TLIF) cages are commonly placed unilaterally, bilateral placement increases the bone graft surface area, optimizes the footprint of the graft, and may improve stability especially in the setting of bilateral facetectomies [4]. Therefore, bilateral placement of TLIF cages may increase the arthrodesis rate, improve lordosis, and optimize construct stability, although there is minimal literature supporting its use for each of these indications.

While unilateral cage placement likely confers less surgical risk to the patient than bilateral cage placement, there is limited and conflicting literature regarding surgical outcomes when comparing bilateral and unilateral cages [5,6]. A prospective randomized controlled trial found that bilateral interbody TLIF cages increased fusion rates but did not significantly influence postoperative patient-reported outcome measures (PROMs), including the Visual Analog Scale [5]. A separate retrospective study found that unilateral cages were less likely to achieve successful arthrodesis, but this had minimal impact on the postoperative PROMs [6]. However, there is little published literature comparing radiographic parameters following unilateral and bilateral cage placement, which may allow us to understand whether one technique is superior in its restoration of sagittal alignment, disc space distraction, or endplate obliquity [6].

Even when expanding the comparisons of bilateral and unilateral cage placement to patients undergoing posterior lumbar interbody fusions, most studies have been limited to small sample sizes [4,7]. Thus, there is no clear evidence to indicate whether bilateral or unilateral cages promote superior radiographic or surgical outcomes in posterior-based spinal fusions. Therefore, the objectives of our study were to (1) compare radiographic alignment between bilateral and unilateral cage placement in TLIF and to (2) determine whether radiographic fusion rates vary between bilateral versus unilateral cage placement.

Materials and Methods

The requirement for informed consent was omitted due to the low risk and retrospective nature of this study. Upon obtaining the institutional review board approval at Thomas Jefferson University (Control #19D.508), patients ≥18 years old who underwent primary or revision one- or two-level TLIF with placement of bilateral interbody cages between 2013–2021 were retrospectively identified. Unilateral and bilateral cages were defined as the use of a single or bilateral bullet cages, respectively, at a single level. For a unilateral cage, it is placed at the patient's symptomatic side, whereas bilateral cages are placed at the lateral margins of the endplate. All bullet cages had similar dimensions (23 mm×9 mm×9 mm). The following Current Procedural Terminology codes for TLIF were included: 22630, ±22632. The exclusion criteria included any patient with a fusion of more than two levels or an indication of infection, malignancy, or trauma. Patients without adequate visualization of the entire lumbar spine on anteroposterior (AP) and lateral lumbar spine radiographs at the preoperative, 6-week postoperative, and 1-year postoperative visits were excluded. The use of unilateral or bilateral interbody cages was left to the discretion of the surgeon. However, soft indications for the use of bilateral interbody cages included possible continued postoperative instability (i.e., bilateral facetectomies especially in the setting of a revision procedure where the patient had bilateral radiculopathy) or when additional lordosis or a greater likelihood of fusion were deemed necessary. For all procedures, local autograft was used to supplement fusion. Bone grafts were placed within the cage, outside the cage in the disc space, and in the lateral gutter contralateral to the TLIF. If bilateral TLIF was performed, no graft was placed in the lateral gutter to minimize bone growth around the exiting nerve root. Determination of bilateral versus unilateral cage and cage material (titanium versus polyetheretherketone [PEEK]) was performed by assessing cage markers on radiographs. Titanium is completely radiopaque, while PEEK cages only have radiopaque markers. The number of cages utilized and their composition were verified by examining the implant records.

1. Data extraction

Patient demographics and surgical characteristics were collected through a structured query language search and manual chart review of the electronic medical records. A 3:1 propensity matching, which controlled for the patients' age, sex, body mass index (BMI), smoking status (non-smoker, current smoker, former smoker), Elixhauser comorbidity index (ECI), and the number of levels fused, was performed. Additionally, the preoperative diagnosis (degenerative spondylolisthesis or isthmic spondylolisthesis) was recorded for each patient. Surgical characteristics collected included revision procedures, number of decompressed and fused levels, and number of levels in which an interbody cage was placed.

Radiographic measurements were collected via our institution's picture archiving and communication system (Sectra AB, Linköping, Sweden). Preoperative, 6-week postoperative, and 1-year postoperative AP and lateral lumbar spine radiographs of each patient were reviewed, and segmental lordosis, anterior disc height, posterior disc height, and endplate obliquity angle were measured. The endplate obliquity was defined as the angle between the superior endplate of the upper vertebrae and the inferior end plate of the lower vertebrae involved in the TLIF on AP radiographs [8,9]. Segmental lordosis was defined as the angle between the upper vertebra's superior endplate and the lower vertebra's inferior endplate on lateral radiographs. If L5–S1 was part of the TLIF, the angle formed by the superior endplates of L5 and S1 were used instead. Disc height was determined by measuring the anterior and posterior intervertebral space of the vertebrae involved in the TLIF. For patients who received interbody cages at two levels, the averages of the anterior and posterior disc heights were calculated. The changes in endplate obliquity, lumbar lordosis, segmental lordosis, anterior disc height, and posterior disc height were defined as delta (Δ) and were calculated by subtracting the preoperative measurement from the 6-week and 1-year postoperative values. Delta measurements were also calculated by subtracting the 6-week postoperative measurement from the 1-year postoperative measurement. The center point ratio (CPR) was defined as the distance between the midpoint of the cage and the middle of the vertebral body. To categorize the placement of each cage, a posteriorly placed cage had a CPR of <0.4, a cage placed in the middle of the vertebral body had a CPR of 0.4< CPR <0.6, and an anteriorly placed cage had a CPR of >0.6. Evidence of radiographic fusion was determined based on bony bridging on AP radiographs, while pedicle screw loosening was determined by the presence of a halo sign on AP and lateral radiographs at the 1-year postoperative visit [10,11].

2. Statistical analysis

Descriptive statistics, including means with standard deviation, were reported for patient demographics, surgical characteristics, and radiographic parameters at the preoperative, 6-week postoperative, and 1-year postoperative follow-up points. The Shapiro-Wilk test was used to analyze the normality of each continuous variable, and parametric data were compared with the independent *t*-test. In contrast, non-parametric data were compared with the Mann-Whitney *U* test. Dichotomous variables were compared with Pearson's chi-square test. Bivariate analyses were conducted using Δ endplate obliquity angle, Δ segmental lordosis, Δ anterior disc height, and Δ posterior disc height between the preoperative and postoperative, preoperative and follow-up, and postoperative and follow-up points. A multivariable logistic regression model was developed to measure the effect of bilateral interbody cage placement on the likelihood of achieving radiographic fusion following TLIF. Statistical significance was set at $p<0.05$. All statistical analyses were performed using R Studio ver. 4.0.2 (RStudio, Boston, MA, USA).

Results

1. Patient demographics

Overall, 46 patients who received bilateral interbody cages were identified and propensity-matched to 138 patients who received a unilateral interbody cage (3:1). There were no significant differences in age ($p=0.408$), sex ($p=0.842$), BMI ($p=0.819$), smoking status ($p=0.814$), and ECI ($p=0.949$) between both groups (Table 1).

2. Surgical characteristics

There was no significant difference in the proportion of patients with a preoperative diagnosis of degenerative spondylolisthesis (67.4% versus 56.6%, $p=0.256$) and isthmic spondylolisthesis (8.7% versus 7.9%, $p=0.768$) between the groups. Furthermore, there was no significant

Table 1. Patient demographics

Characteristic	Unilateral cage (N=138)	Bilateral cages (N=46)	*p*-value[a)]
Age (yr)	64.2±9.72	63.0±8.61	0.408
Sex			0.842
Female	32 (23.2)	12 (26.1)	
Male	106 (76.8)	34 (73.9)	
Body mass index (kg/m^2)	35.1±7.92	35.4±6.75	0.819
Smoking status			0.814
Non-smoker	96 (69.6)	30 (65.2)	
Current smoker	15 (10.9)	5 (10.9)	
Former smoker	27 (19.6)	11 (23.9)	
Elixhauser comorbidity index	1.84±1.36	1.83±1.30	0.949

Values are presented as mean±standard deviation or number (%).
[a)]By independent *t*-test, Mann-Whitney *U* test, or Pearson's chi-square test.

difference in the proportion of patients who underwent revision TLIF between the groups (19.6% versus 10.9%, p=0.261). The average number of levels decompressed (1.80 versus 2.09, p=0.098) and fused (1.87 versus 1.83, p=0.779) were also not significantly different between the groups. The average follow-up time for the 6-week (36.9 days versus 29.1 days, p=0.542) and 1-year postoperative radiographs (440 days versus 456 days, p=0.786) were not significantly different between the groups. Cage placement in bilateral TLIFs were less likely to be posterior (p=0.004), while there were no significant differences in the cage material between the groups (p=0.115) (Table 2).

3. Radiographic outcomes

Compared with patients who received a unilateral interbody cage, those who received bilateral interbody cages had significantly lower preoperative disc heights in both

Table 2. Surgical characteristics

Variable	Unilateral cage (N=138)	Bilateral cages (N=46)	*p*-value[a)]
Preoperative diagnosis			
Isthmic spondylolisthesis			0.768
No	140 (92.1)	42 (91.3)	
Yes	12 (7.89)	4 (8.70)	
Degenerative spondylolisthesis			0.256
No	66 (43.4)	15 (32.6)	
Yes	86 (56.6)	31 (67.4)	
Revision procedure			0.261
No	111 (80.4)	41 (89.1)	
Yes	27 (19.6)	5 (10.9)	
No. of levels decompressed	2.09±1.03	1.80±0.98	0.098
No. of levels fused	1.87±0.93	1.83±0.90	0.779
No. of TLIF levels	1.31±0.51	1.20±0.40	0.111
Days after surgery for follow-up X-ray	456±426	440±314	0.786
Days after surgery for postoperative X-ray	29.1±63.0	36.9±78.1	0.542
Cage positioning			0.004*
Posterior	13 (9.42)	0	
Middle	69 (50.0)	16 (34.8)	
Anterior	56 (40.6)	30 (65.2)	
Cage material			0.115
PEEK	129 (93.5)	46 (100.0)	
Titanium	9 (6.52)	0	

Values are presented as number (%) or mean±standard deviation.
TLIF, transforaminal lumbar interbody fusion; PEEK, polyetheretherketone.
*p<0.05 (statistical significance). [a)]By independent *t*-test, Mann-Whitney *U* test, or Pearson's chi-square test.

the anterior (8.18 mm versus 10.3 mm, p=0.001) and posterior (5.93 mm versus 7.81 mm, p<0.001) disc spaces. The 6-week and 1-year postoperative disc heights in both the anterior and posterior disc spaces were not significantly different between the groups. From the preoperative to 6-week postoperative points, the anterior (2.70 mm versus 5.57 mm, p<0.001) and posterior Δ disc heights (2.26 mm versus 4.63 mm, p<0.001) were significantly greater in patients who received bilateral interbody cages. However, from the 6-week to the 1-year postoperative points, the Δ disc height was only significantly greater in the posterior disc space in patients who received bilateral interbody cages (−0.59 mm versus −1.06 mm, p=0.028) (Table 3).

Patients who received bilateral interbody cages had significantly greater preoperative endplate obliquity angles (5.33°±5.31° versus 2.24°±2.84°, p<0.001) and segmental lordosis (20.2°±10.4° versus 16.4°±8.66°, p<0.017). However, the endplate obliquity angle and Δ segmental lordosis measurements were not significantly different at the 6-week and 1-year postoperative time points. Patients

Table 3. Disk height

Variable	Unilateral cage (N=138)	Bilateral cages (N=46)	p-value[a)]
Anterior disc height			
Preoperative anterior disc height (mm)	10.3±3.55	8.18±3.66	0.001*
Postoperative anterior disc height (mm)	13.10±2.67	13.80±2.79	0.150
Final follow-up anterior disc height (mm)	12.10±2.56	12.70±3.03	0.213
Δ Preoperative to 6-week postoperative, anterior disc height (mm)	2.70±3.56	5.57±3.78	<0.001*
Δ 6-week follow-up to final follow-up, anterior disc height (mm)	-1.01±1.33	-1.06±2.56	0.891
Posterior disc height			
Preoperative posterior disc height (mm)	7.81±2.96	5.93±2.32	<0.001*
Postoperative posterior disc height (mm)	10.10±2.49	10.60±2.17	0.213
Final follow-up posterior disc height (mm)	9.48±2.44	9.50±1.82	0.945
Δ Preoperative to 6-week postoperative, posterior disc height (mm)	2.26±3.74	4.63±2.87	<0.001*
Δ 6-week follow-up to final follow-up, posterior disc height (mm)	-0.59±1.16	-1.06±1.25	0.028*

Values are presented as mean±standard deviation.
*p<0.05 (statistical significance). [a)]By independent t-test or Mann-Whitney U test.

Table 4. Angular measurements

Variable	Unilateral cage (N=138)	Bilateral cages (N=46)	p-value[a)]
Endplate obliquity (°)			
Preoperative endplate obliquity angle	5.33±5.31	2.24±2.84	<0.001*
Postoperative endplate obliquity angle	3.30±3.51	2.55±2.75	0.139
Final follow-up endplate obliquity angle	3.31±3.71	2.48±3.16	0.143
Δ Preoperative to 6-week postoperative endplate obliquity angle (°)	-2.03±4.23	0.30±2.99	<0.001*
Δ Preoperative to final follow-up endplate obliquity angle (°)	-2.02±4.42	0.24±2.81	<0.001*
Segmental lordosis (°)			
Preoperative segmental lordosis angle	20.2±10.4	16.4±8.66	0.017*
Postoperative segmental lordosis angle	18.6±8.50	22.1±15.7	0.150
Final follow-up segmental lordosis angle	18.5±8.48	19.7±8.98	0.427
Δ Preoperative to 6-week postoperative segmental lordosis (°)	-1.57±10.9	5.74±14.1	0.002*
Δ Preoperative to final follow-up segmental lordosis (°)	-1.64±11.2	3.32±7.21	0.001*

Values are presented as mean±standard deviation.
*p<0.05 (statistical significance). [a)]By independent t-test or Mann-Whitney U test.

who received bilateral interbody cages had a significantly greater Δ endplate obliquity angle at the 6-week (0.30 °±2.99° versus −2.03°±4.23°, p<0.001) and 1-year (0.24°±2.81° versus −2.02°±4.42°, p<0.001) postoperative points. Furthermore, patients who received bilateral interbody cages had a significantly greater Δ segmental lordosis at the 6-week (5.74°±14.1° versus −1.57°±10.9°, p=0.002) and 1-year (3.32°±7.21° versus −1.64°±11.2°, p=0.001) postoperative points (Table 4). Additionally, there was a significantly higher rate of fusion at the 1-year postoperative point (89.1% versus 70.3%, p=0.018) in patients who received bilateral interbody cages (Table 5).

Sub-analysis determined that anterior, posterior, or middle cage positioning was not predictive of segmental lordosis restoration (p=0.393), anterior disc height loss (p=0.237), or posterior disc height loss (p=0.531) (Appendix 1).

4. Multivariable logistic regression analysis

Multivariable logistic regression analysis revealed that receiving bilateral interbody cages (estimate, 1.35; odds ratio, 3.87; 95% confidence interval, 1.51–12.05; p=0.010) was a significant predictor of fusion as detected on AP lumbar spine radiographs at the 1-year postoperative point. Meanwhile, age, sex, BMI, smoking status, ECI, and the number of levels were not significant positive or negative predictors of fusion (p>0.05) (Table 6). Multivariable analysis of segmental lordosis revealed that bilateral cage placement increased segmental lordosis (p=0.010); however, segmental lordosis was not correlated with cage placement in an anterior or posterior position (p>0.05). Additionally, bilateral cage placement was a predictor of posterior disc height loss (estimate, 0.454; p=0.032) (Appendix 2).

Table 5. Radiographic evidence of fusion

	Unilateral cage (N=138)	Bilateral cages (N=46)	p-value[a)]
Radiographic evidence of fusion[b)]			0.018*
No	41 (29.7)	5 (10.9)	
Yes	97 (70.3)	41 (89.1)	

Values are presented as number (%).
*p<0.05 (statistical significance). [a)]By Pearson's chi-square test. [b)]As defined by bone bridging and screw loosening on anteroposterior and lateral radiograph.

Table 6. Multivariable logistic regression analysis

Predictors	Radiographic evidence of fusion		
	Estimate	OR (95% CI)	p-value[a)]
Age	0.02	1.03 (0.98–1.07)	0.248
Male sex	0.80	2.24 (0.93–5.38)	0.071
Body mass index	0.015	1.01 (0.97–1.07)	0.557
Elixhauser comorbidity index	0.18	1.20 (0.91–1.61)	0.201
Smoking status			
Non-smoker	Reference		
Current smoker	0.16	1.18 (0.39–4.13)	0.783
Former smoker	-0.32	0.73 (0.31–1.80)	0.481
Bilateral cages	1.35	3.87 (1.51–12.05)	0.010*
No. of TLIF levels	0.047	1.05 (0.71–1.58)	0.817

OR, odds ratio; CI, confidence interval; TLIF, transforaminal lumbar interbody fusion.
*p<0.05 (statistical significance). [a)]By multiple logistic regression.

Discussion

TLIFs are performed to restore neuroforaminal height and sagittal balance of the lumbar spine. However, few studies have analyzed the differences in radiographic alignment between bilateral and unilateral interbody TLIF cages. While some studies suggest that bilateral cages promote greater arthrodesis rates, the improved fusion rate does not affect clinical outcomes [5,6]. However, none of the previous studies have provided robust radiographic data describing whether a unilateral or bilateral cage promotes improved segmental lordosis or endplate obliquity angles. Given the paucity of evidence, additional analyses documenting the radiographic alignment of the lumbar spine following unilateral or bilateral cage placement in TLIF are warranted. The results of our study suggest that bilateral interbody cage placement is more likely to restore segmental lordosis compared to unilateral interbody cage placement, while endplate obliquity was more likely to be restored following unilateral interbody cage placement. Similar to previous studies, bilateral interbody cage placement significantly increased the likelihood of fusion. Surprisingly, we also observed a greater degree of subsidence in the posterior aspect of the interbody space in patients with bilateral interbody cages, which is likely due to the greater amount of disc space correction achieved intraoperatively [6,12,13].

Previous literature reported a positive correlation between improved lumbar sagittal balance and reduced postoperative pain [3,14-16]. Therefore, optimizing the restoration of lordosis during TLIF may be an important goal of surgery [3,17-19]. However, prior studies analyzing the effect of unilateral interbody TLIFs on lordosis improvement have obtained mixed results. While some studies indicate that TLIFs effectively restore segmental and lumbar lordosis, others have found that TLIFs produce net neutral or overall kyphotic segmental alignment [3,15,17,20-22]. While most of these studies are based on unilateral TLIF cage placement, our study found that segmental lordosis increased by 3.32° at the 1-year postoperative point in patients in whom a bilateral body cage was placed, whereas unilateral body cage placement resulted in kyphosis by an average of 1.62°. Given that bilateral interbody cages provide a larger surface area to bolster the vertebral column, bilateral cages may be more effective at achieving and maintaining the corrected lordosis [3,18,19].

Unilateral interbody cages are associated with improved endplate obliquity of the affected spinal segment [23]. For patients with degenerative lumbar scoliosis, Zhu et al. [23] found that the endplate obliquity was minimized after unilateral TLIFs. Similar results were obtained by Zhao et al. [24], who utilized sequential TLIF procedures to correct coronal imbalance in patients with degenerative scoliosis. Similarly, our study observed a significant decrease in endplate obliquity in patients who received unilateral TLIF cages.

For both endplate obliquity angles and segmental lordosis measurements, differences in the underlying surgical indications likely caused variance in the unilateral and bilateral preoperative radiographic measurements. Patients with a more pronounced endplate obliquity were more likely to receive a unilateral TLIF cage to correct the coronal lumbar curve. Additionally, bilateral interbody cages were more likely to be selected when there was a concern for spinal instability [25]. Therefore, our study suggests that patients requiring improved lordotic correction may receive greater benefit with bilateral interbody devices.

The average loss of disc height following interbody cage placement is believed to range between 0.5 mm and 0.75 mm [3,26,27]. Our study found similar anterior disc height loss regardless of unilateral or bilateral TLIF cage placement (approximately 1 mm), but there was slightly greater posterior disc height loss in patients with bilateral cages. Given the increased surface area provided by bilateral interbody cages, less disc height collapse was expected. It is hypothesized that the improved disc height correction obtained in the bilateral cage group resulted in greater compressive forces across the interbody device, possibly due to additional ligamentous tension or disc space over-distraction. Since the difference in posterior disc height loss between unilateral and bilateral cages was only 0.47 mm at the 6-week postoperative point, this be attributed to measurement error and is unlikely to be clinically relevant.

One purported benefit of bilateral TLIF is an increased likelihood of successful bony arthrodesis, which was observed in our retrospective study [5,6]. One theory behind the increased fusion rates is enhanced dynamic stabilization; however, previous studies have not identified any biomechanical differences between unilateral and bilateral TLIF cage placement [6,28]. Therefore, the improved arthrodesis rates may be due to the additional bone grafting surface area provided by the second cage, which optimizes the ability for the construct to fuse.

Limitations to our study include those inherent to any retrospective review. Although patients were systematically included in the study, they were identified based on the availability of preoperative, 6-week postoperative, and 1-year postoperative data following the index TLIF, which may have introduced a selection bias. Additionally, we did not consider the impact of interbody sagittal location on lordotic correction, which may have affected segmental lordosis measurements. Further, our analysis of radiographic fusion was limited to AP radiographs. While this is a less sensitive and specific assessment compared to computed tomography (CT), this technique has been validated in several previous studies, and we do not routinely obtain postoperative CT scans unless a potential symptomatic pseudarthrosis exists [10,29]. Additionally, TLIFs were performed by several different surgeons at our institution, introducing variability in surgical technique and postoperative care which may have influenced clinical and radiographic outcomes; however, this may ultimately increase the generalizability of the study. Lastly, it is important to note that previous studies have reported a margin of error of 8° for Cobb angle measurements made on AP radiographs [8,9,30]. All angular measurements in our study were made using the Cobb method, and all Δ were found to be <8°. As previously discussed, the differences in disc height loss were within human measurement errors, which may not be clinically relevant. Additionally, the significant differences in the Δ postoperative endplate obliquity angle and segmental lordosis may be due to margin of error measurements.

Conclusions

TLIFs with bilateral cages resulted in greater improvement in segmental lordosis and bony arthrodesis, while unilateral cages were more likely to affect endplate obliquity. Given that this is one of the few studies comparing radiographic outcomes between unilateral and bilateral cages in patients undergoing TLIF procedures, additional high-quality prospective studies are needed to verify the results of the present study and add further context to whether the improvements in segmental lordosis and endplate obliquity result in greater long-term clinical outcomes.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

ORCID

Mark James Lambrechts: https://orcid.org/0000-0002-9106-2228
Jeremy Heard: https://orcid.org/0000-0001-5181-3966
Nicholas D'Antonio: https://orcid.org/0000-0001-8484-0207
John Bodnar: https://orcid.org/0000-0003-3470-9619
Gregory Schneider: https://orcid.org/0000-0003-2210-433X
Evan Bloom: https://orcid.org/0000-0001-8423-5699
Jose Canseco: https://orcid.org/0000-0002-2152-5725
Barrett I. Woods: https://orcid.org/0000-0002-4136-3612
IIan David Kaye: https://orcid.org/0000-0003-4058-0372
Mark Kurd: https://orcid.org/0000-0001-9680-1088
Jeffrey Rihn: https://orcid.org/0000-0002-0423-3675
Alan Hilibrand: https://orcid.org/0000-0001-8811-9687
Gregory Schroeder: https://orcid.org/0000-0001-8811-9687
Alexander Vaccaro: https://orcid.org/0000-0002-8073-0796
Christopher Kepler: https://orcid.org/0000-0002-0996-4346

Author Contributions

Conceptualization: MJL; formal analysis: JH, NDA; methodology: MJL, JH, NDA; visualization: MJL, JH, NDA; data curation: JH, NDA, JB, GS, EB; writing-original draft: MJL, JH; writing-review & editing: MJL, JH, NDA, AH, AV, CK; and final approval of the manuscript: all authors.

References

1. Martin BI, Mirza SK, Spina N, Spiker WR, Lawrence B, Brodke DS. Trends in lumbar fusion procedure rates and associated hospital costs for degenerative spinal diseases in the United States, 2004 to 2015. Spine (Phila Pa 1976) 2019;44:369-76.
2. Schmoelz W, Keiler A. Intervertebral cages from a biomechanical point of view. Orthopade 2015;44:132-7.
3. Kepler CK, Rihn JA, Radcliff KE, et al. Restoration of lordosis and disk height after single-level transforaminal lumbar interbody fusion. Orthop Surg 2012;4:15-20.
4. Fogel GR, Toohey JS, Neidre A, Brantigan JW. Is one cage enough in posterior lumbar interbody fusion: a comparison of unilateral single cage interbody fusion to bilateral cages. J Spinal Disord Tech 2007;20:60-5.
5. Aoki Y, Yamagata M, Ikeda Y, et al. A prospective randomized controlled study comparing transforaminal lumbar interbody fusion techniques for degenerative spondylolisthesis: unilateral pedicle screw and 1 cage versus bilateral pedicle screws and 2 cages. J Neurosurg Spine 2012;17:153-9.
6. Lynch CP, Cha ED, Rush Iii AJ, et al. Outcomes of transforaminal lumbar interbody fusion using unilateral versus bilateral interbody cages. Neurospine 2021;18:854-62.
7. Lee JH, Lee JH, Yoon KS, Kang SB, Jo CH. Comparative study of unilateral and bilateral cages with respect to clinical outcomes and stability in instrumented posterior lumbar interbody fusion. Neurosurgery 2008;63:109-14.
8. Geijer H, Verdonck B, Beckman KW, Andersson T, Persliden J. Digital radiography of scoliosis with a scanning method: radiation dose optimization. Eur Radiol 2003;13:543-51.
9. Geijer H, Beckman K, Jonsson B, Andersson T, Persliden J. Digital radiography of scoliosis with a scanning method: initial evaluation. Radiology 2001;218:402-10.
10. Christensen FB, Laursen M, Gelineck J, Eiskjaer SP, Thomsen K, Bunger CE. Interobserver and intraobserver agreement of radiograph interpretation with and without pedicle screw implants: the need for a detailed classification system in posterolateral spinal fusion. Spine (Phila Pa 1976) 2001;26:538-44.
11. Wu X, Shi J, Wu J, et al. Pedicle screw loosening: the value of radiological imagings and the identification of risk factors assessed by extraction torque during

screw removal surgery. J Orthop Surg Res 2019;14:6.
12. Ren C, Qin R, Sun P, Wang P. Effectiveness and safety of unilateral pedicle screw fixation in transforaminal lumbar interbody fusion (TLIF): a systematic review and meta-analysis. Arch Orthop Trauma Surg 2017;137:441-50.
13. Choi UY, Park JY, Kim KH, et al. Unilateral versus bilateral percutaneous pedicle screw fixation in minimally invasive transforaminal lumbar interbody fusion. Neurosurg Focus 2013;35:E11.
14. Xu DS, Bach K, Uribe JS. Minimally invasive anterior and lateral transpsoas approaches for closed reduction of grade II spondylolisthesis: initial clinical and radiographic experience. Neurosurg Focus 2018;44:E4.
15. 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:E10.
16. Turner JD, Akbarnia BA, Eastlack RK, et al. Radiographic outcomes of anterior column realignment for adult sagittal plane deformity: a multicenter analysis. Eur Spine J 2015;24 Suppl 3:427-32.
17. Mummaneni PV, Hussain I, Shaffrey CI, et al. The minimally invasive interbody selection algorithm for spinal deformity. J Neurosurg Spine 2021 Mar 12 [Epub]. https://doi.org/10.3171/2020.9.SPINE20230
18. Dimar JR 2nd, Glassman SD, Vemuri VM, Esterberg JL, Howard JM, Carreon LY. Lumbar lordosis restoration following single-level instrumented fusion comparing 4 commonly used techniques. Orthopedics 2011;34:e760-4.
19. 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;82:289-98.
20. Divi SN, Schroeder GD, Goyal DK, et al. Fusion technique does not affect short-term patient-reported outcomes for lumbar degenerative disease. Spine J 2019;19:1960-8.
21. Watkins RG 4th, Hanna R, Chang D, Watkins RG 3rd. Sagittal alignment after lumbar interbody fusion: comparing anterior, lateral, and transforaminal approaches. J Spinal Disord Tech 2014;27:253-6.
22. 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;7:379-86.
23. Zhu Y, Wang B, Wang H, Jin Z, Zhu Z, Liu H. Long-term clinical outcomes of selective segmental transforaminal lumbar interbody fusion combined with posterior spinal fusion for degenerative lumbar scoliosis. ANZ J Surg 2014;84:781-5.
24. Zhao Y, Liang Y, Mao K. Radiographic and clinical outcomes following MIS-TLIF in patients with adult lumbar degenerative scoliosis. J Orthop Surg Res 2018;13:93.
25. Sparrey CJ, Bailey JF, Safaee M, et al. Etiology of lumbar lordosis and its pathophysiology: a review of the evolution of lumbar lordosis, and the mechanics and biology of lumbar degeneration. Neurosurg Focus 2014;36:E1.
26. Kim SB, Jeon TS, Heo YM, et al. Radiographic results of single level transforaminal lumbar interbody fusion in degenerative lumbar spine disease: focusing on changes of segmental lordosis in fusion segment. Clin Orthop Surg 2009;1:207-13.
27. Jagannathan J, Sansur CA, Oskouian RJ Jr, Fu KM, Shaffrey CI. Radiographic restoration of lumbar alignment after transforaminal lumbar interbody fusion. Neurosurgery 2009;64:955-64.
28. Ambati DV, Wright EK Jr, Lehman RA Jr, Kang DG, Wagner SC, Dmitriev AE. Bilateral pedicle screw fixation provides superior biomechanical stability in transforaminal lumbar interbody fusion: a finite element study. Spine J 2015;15:1812-22.
29. Gotfryd AO, Pomar Fde M, Carneiro Neto NJ, Franzin FJ, Rodrigues LM, Poletto PR. Reliability analysis of radiographic methods for determination of posterolateral lumbossacral fusion. Einstein (Sao Paulo) 2014;12:198-203.
30. Gstoettner M, Sekyra K, Walochnik N, Winter P, Wachter R, Bach CM. Inter- and intraobserver reliability assessment of the Cobb angle: manual versus digital measurement tools. Eur Spine J 2007;16:1587-92.

Appendix 1. Cage position and its association with segmental lordosis and disc height changes

Variable	Posterior (N=13)	Middle (N=85)	Anterior (N=86)	*p*-value[a)]
Bilateral cages in TLIF				0.004*
No	13 (100.0)	69 (81.2)	56 (65.1)	
Yes	0	16 (18.8)	30 (34.9)	
Segmental lordosis				
Preoperative segmental lordosis angle (°)	23.4±13.1	19.6±10.1	18.2±9.53	0.196
Postoperative segmental lordosis angle (°)	21.4±9.41	19.0±8.55	19.7±12.9	0.738
Final follow-up segmental lordosis angle (°)	20.6±9.81	18.8±8.43	18.6±8.66	0.728
Δ Preoperative to 6-week postoperative segmental lordosis (°)	-2.01±8.64	-0.67±10.9	1.52±13.6	0.529
Δ Preoperative to final follow-up segmental lordosis (°)	-2.76±6.29	-0.85±11.5	0.39±10.2	0.393
Anterior disc height				
Preoperative anterior disc height (mm)	9.79±3.25	10.5±3.67	9.19±3.71	0.076
Postoperative anterior disc height (mm)	13.8±3.36	13.3±2.64	13.2±2.69	0.751
Final follow-up anterior disc height (mm)	12.3±3.85	12.1±2.32	12.3±2.87	0.893
Δ 6-week follow-up to final follow-up, anterior disc height (mm)	-1.62±1.27	-1.12±1.76	-0.83±1.72	0.237
Posterior disc height				
Preoperative posterior disc height (mm)	7.94±4.79	7.64±2.88	6.98±2.59	0.254
Postoperative posterior disc height (mm)	10.8±2.58	9.98±2.20	10.4±2.58	0.387
Final follow-up posterior disc height (mm)	9.87±2.97	9.33±2.13	9.60±2.35	0.628
Δ 6-week follow-up to final follow-up, posterior disc height (mm)	-0.98±0.83	-0.62±1.17	-0.76±1.27	0.531

Values are presented as number (%) or mean±standard deviation.
TLIF, transforaminal lumbar interbody fusion.
*p<0.05 (statistical significance). [a)]By Pearson's chi-square test.

Appendix 2. Multivariable analysis of segmental lordosis and posterior disc height at final follow-up

Predictors	Estimate	*p*-value[a)]
Correction of segmental lordosis		
Bilateral cages	-4.751	0.010*
Cage position		
Posterior	Ref	
Middle	-1.010	0.747
Anterior	-1.492	0.639
Posterior disc height loss		
Titanium cages	-0.723	0.079
Bilateral cages	0.454	0.032*
Cage placement		
Posterior	Ref	
Middle	-0.327	0.360
Anterior	-0.182	0.611

Ref, reference.
*p<0.05 (statistical significance). [a)]By multiple logistic regression.