World Neurosurgery: X 31 (2026) 100604

Contents lists available at ScienceDirect

World Neurosurgery: X

journal homepage: www.journals.elsevier.com/world-neurosurgery-x

# Clinical and radiological outcomes following biportal endoscopic lumbar interbody fusion: A comparative study of three interbody cage strategies

Ju-Eun Kim [a], Hee Soo Kim [b], Daniel K. Park [c,*]

[a] Department of Orthopaedic Surgery, Baroseomyeon Hospital, Pusan, South Korea
[b] Yonsei University College of Medicine, Seoul, South Korea
[c] Midwest Orthopedics at RUSH, Chicago, IL, United States

ARTICLE INFO

*Keywords:*
Spinal stenosis
Spondylolisthesis
Biportal
Endoscopic
Cage
Lumbar interbody fusion

ABSTRACT

*Background:* While traditional open fusions yield high fusion rates, they can result in significant muscle damage. Biportal Endoscopic Lumbar Interbody Fusion (BELIF) has emerged. This study compares clinical and radiological outcomes of BELIF using three different interbody cage strategies.

*Methods:* This retrospective cohort study included 106 consecutive patients undergoing single-segment BELIF for lumbar degenerative disease. Patients were divided into three groups based on cage strategy: Group A ($n = 34$, two 28 × 10 mm Titanium cages), Group B ($n = 32$, single 40 × 15 mm PEEK cage), and Group C ($n = 40$, single 32 × 10 mm PEEK cage). Clinical outcomes and radiological outcomes were assessed preoperatively and at final follow-up.

*Results:* All groups showed significant improvements in VAS and ODI scores, with no significant intergroup differences in final scores. Group B had the longest operative time ($p < 0.001$). No major neurological complications occurred. While sagittal parameters improved within groups, there were no significant intergroup differences in the degree of correction. Fusion rates differed significantly at 6 and 12 months (Groups A & B > Group C) but were not significantly different at final follow-up ($p = 0.845$). The incidence of subsidence was significantly higher in Group C (15.0%) compared to Group A (5.9%) and Group B (6.3%) ($p = 0.035$)

*Conclusion:* BELIF provide satisfactory clinical outcomes regardless of the cage strategy. However, cage size and potentially material significantly influenced early fusion rates and subsidence. Cages with larger footprints demonstrated superior early fusion, whereas the smallest footprint cage was associated with a significantly higher subsidence rate.

## 1. Introduction

Degenerative lumbar disease is a major cause of low back pain and functional disability worldwide. For patients who do not respond to conservative treatment or present with neurological deficits and segmental instability, lumbar fusion is the typical surgical recommendation.[1] Traditional techniques include segmental fixation without interbody application; however, to increase fusion rates, surgeons have implemented open posterior lumbar interbody fusion and transforaminal interbody fusion.[1] However, these approaches are associated with significant drawbacks due to their extensive collateral damage to the normal musculature resulting in high estimated blood loss, prolonged recovery time, and increased postoperative pain.[2]

Minimally Invasive Transforaminal Lumbar Interbody Fusion (MI-TLIF) was introduced to mitigate these soft-tissue complications. Nonetheless, MI-TLIF, often utilizing tubular retractors, presented limitations such as a narrow working corridor and restricted visualization.[3–5] Recently, the Unilateral biportal endoscopic(UBE) technique has advanced in the field of spinal surgery. Unlike conventional uniportal endoscopic surgery, UBE utilizes independent portals for the endoscope (viewing) and surgical instruments (working). These two independent portals allow for continuous fluid irrigation and free movement of the surgical view and instruments, enabling surgeons to perform procedures with a relatively short learning curve.[6,7] UBE techniques have been reported to provide clinical outcomes comparable to microscopic surgery while offering several advantages, including reduced postoperative pain, facilitated early rehabilitation, minimized muscle injury, decreased intraoperative blood loss, and shortened

* Corresponding author. Department of Orthopaedic Surgery., 1611 W Harrison St, Chicago, IL, 60612, United States.
*E-mail addresses:* dspfuture@hanmail.net (J.-E. Kim), hscandoall@naver.com (H.S. Kim), daniel.park@rushortho.com (D.K. Park).

https://doi.org/10.1016/j.wnsx.2026.100604
Received 20 December 2025; Received in revised form 23 March 2026; Accepted 22 May 2026
Available online 27 May 2026

hospital stays.[8,9] These advantages of the UBE technique have been applied to lumbar interbody fusion, leading to the development of Biportal Endoscopic Lumbar Interbody Fusion (BELIF).

In successful lumbar interbody fusion, the interbody cage plays a crucial role in providing structural support until fusion occurs. However, cage subsidence is a common complication that can lead to loss of indirect decompression, nonunion, and need for revision surgery. Various factors influence cage subsidence, including bone mineral density, endplate preparation, cage size and footprint, and cage material (PEEK vs. Titanium).[10,11] Therefore, utilizing a cage with a larger footprint to distribute the load onto the stronger peripheral endplate can potential decrease the risk for subsidence. While various cage strategies (size, number, material) are being explored in BELIF, there is a lack of research directly comparing three different types of cages to analyze their impact on clinical and radiological outcomes, particularly fusion and subsidence rates. Therefore, the purpose of this study is to compare the postoperative clinical and radiological outcomes (sagittal balance, fusion rate and subsidence rate) in patients who underwent BETLIF using three distinct interbody cages, two small titanium cages, one large PEEK cage, and one small PEEK cage.

## 2. Material and method

### 2.1. Study design and patient population

A retrospective cohort study was performed on 106 consecutive patients treated with single-segment biportal endoscopic lumbar interbody fusion (BELIF) for lumbar degenerative disease. All procedures were conducted at a single center from January 2018 to June 2023. All patients provided written informed consent, and the study was approved by the Institutional Review Board with approval 2025-10-009. Only patients who presented with intractable claudication and/or neurological symptoms persisting for at least three months were included. All patients had pathology confined to a single segment. All patients were followed a minimum of 2 years. The exclusion criteria included patients with evidence of active spinal infection or tumor, as well as those with a history of previous spinal instrumentation at the index level.

Patients were divided into three groups based on the interbody cage strategy utilized. Patients who underwent BELIF with two 28 × 10 mm Titanium cages were in Group A ($n = 34$). Patients who received a single 40 × 15 mm PEEK cage ($n = 32$) were in Group B. Lastly, patients who had a small 32 mm length x 10 mm width PEEK cage were in Group C ($n = 40$).

Clinical parameters were evaluated pre-operatively, and at the final follow-up examination. These assessments included the Visual Analog Scale (VAS) for leg and back pain and the Oswestry Disability Index (ODI) score. Additionally, perioperative data, including operative time and time to ambulation, were obtained. Patients underwent radiological evaluation at 6-month intervals. These assessments consisted of standing whole-spine anteroposterior (AP) and lateral plain radiographs, as well as computed tomography (CT) scans of the lumbar spine. Fusion status was assessed according to the Bridwell Interbody Fusion Grading System. Successful fusion was defined as Bridwell grades I or II. The incidence and severity of cage subsidence were assessed using the Marchi classification system on computed tomography (CT) scans.[12] Sagittal alignment parameters, including lumbar lordosis (LL), sacral slope (SS), pelvic tilt (PT), C7-S1 Sagittal Vertical Axis (SVA), segmental lordosis of the index level, and the pelvic incidence-lumbar lordosis (PI-LL) mismatch, were assessed pre-operatively and final follow up postoperatively.

### 2.2. Operation technique

BELIF technique has been previously described.[13] In brief, the patient was placed in a prone position with the abdomen free to preserve neutral lumbar lordosis. Continuous gravity-flow irrigation was maintained using a normal saline bag suspended 1.7 m above floor level, obviating the need for an infusion pump. Incision sites were planned and marked under true anteroposterior (AP) fluoroscopic guidance. Subsequently, two 2-cm transverse skin incisions were created to facilitate the triangulation technique. Decompression commenced with a laminectomy, initiated by a high-speed burr and completed with a Kerrison rongeur to remove the lamina and underlying ligamentum flavum. A chisel or osteotome was employed for the ipsilateral facetectomy to harvest local autologous bone graft, which was set aside for interbody fusion. Sublaminar contralateral decompression was performed only as necessary to ensure adequate release of the neural elements. After decompression was finished, attention was directed to the disc preparation. The disc material was meticulously excised under high-magnification endoscopic visualization. Finally, serial tapered trials were inserted to confirm the optimal intervertebral height and trajectory for cage implantation. A funnel was introduced into the anterior disc space under fluoroscopic guidance, facilitating the targeted delivery of the locally harvested autograft and demineralized bone matrix. Subsequently, the interbody cage was inserted via the working portal eliminating the need for supplementary incisions. The interbody cages utilized were specific to each group: Group A: Two 28 mm (length) x 10 mm (width) Titanium cages (Adaptix™, Medtronics, USA). Group B: A single 40 mm (length) x 15 mm (width) cage (Voyage™, Endovision, Korea). Group C: A single 32 mm (length) x 10 mm (width) PEEK cage (Capstone™, Medtronics, USA) (Fig. 1). After satisfactory cage position was confirmed fluoroscopically, hemostasis was meticulously conducted to mitigate the risk of postoperative epidural hematoma. Ipsilateral percutaneous pedicle screw fixation was performed utilizing the established viewing and working portals. For contralateral fixation, incisions similar to the ipsilateral portals were made. A drain was inserted into the epidural space before final wound closure (Fig. 2).

### 2.3. Statistical analysis

All statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS) version 22.0 (SPSS Inc., Chicago, IL, USA). Continuous variables are presented as mean standard deviation (SD). Categorical variables were analyzed using the chi-squared test. The paired *t*-test was utilized for pre- and post-operative comparisons within groups, while one-way analysis of variance (ANOVA) was used for intergroup comparisons. A $p$-value $<0.05$ was considered statistically significant.

## 3. Result

### 3.1. Demographics

A total of 106 consecutive patients were included in the final analysis, comprising 34 patients in Group A, 32 patients in Group B, and 40 patients in Group C. The three groups were found to be comparable in terms of mean age and sex distribution. The ratio of primary to revision cases was 10:24 in Group A, 17:15 in Group B, and 25:15 in Group C. There was a statistically significant difference in the distribution of primary versus revision cases among the three groups as Group C had a higher proportion of primary cases and Group A had more revisions ($p = 0.009$). The follow-up period was different for Group A, Group B, and Group C, but at least 2 year minimum follow up was available for all patients ($p = 0.000$).

The operative level was mainly at L4-5 in all three groups (50-64.7% of each group). The difference in preoperative diagnosis was not statistically significant in all three groups. ($p = 0.745$) A statistically significant difference was observed in the mean operative time per level ($p < 0.001$). Group B (138.91 ± 8.59 min) had the longest duration, compared to Group A (116.03 ± 11.27 min) and Group C (120.88 ± 15.19 min).Time to ambulation also differed significantly among the groups ($p < 0.001$), with Group C demonstrating the longest mean time

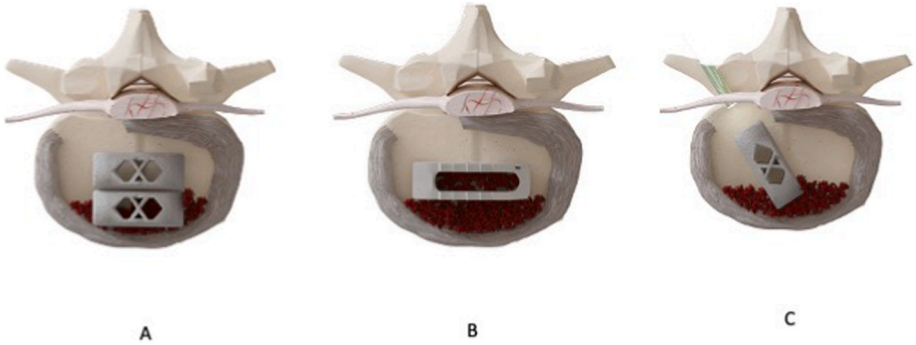


**Fig. 1.** Three different cage strategies used. A) Two titanium small cages B) Large PEEK cage C) small PEEK cage.

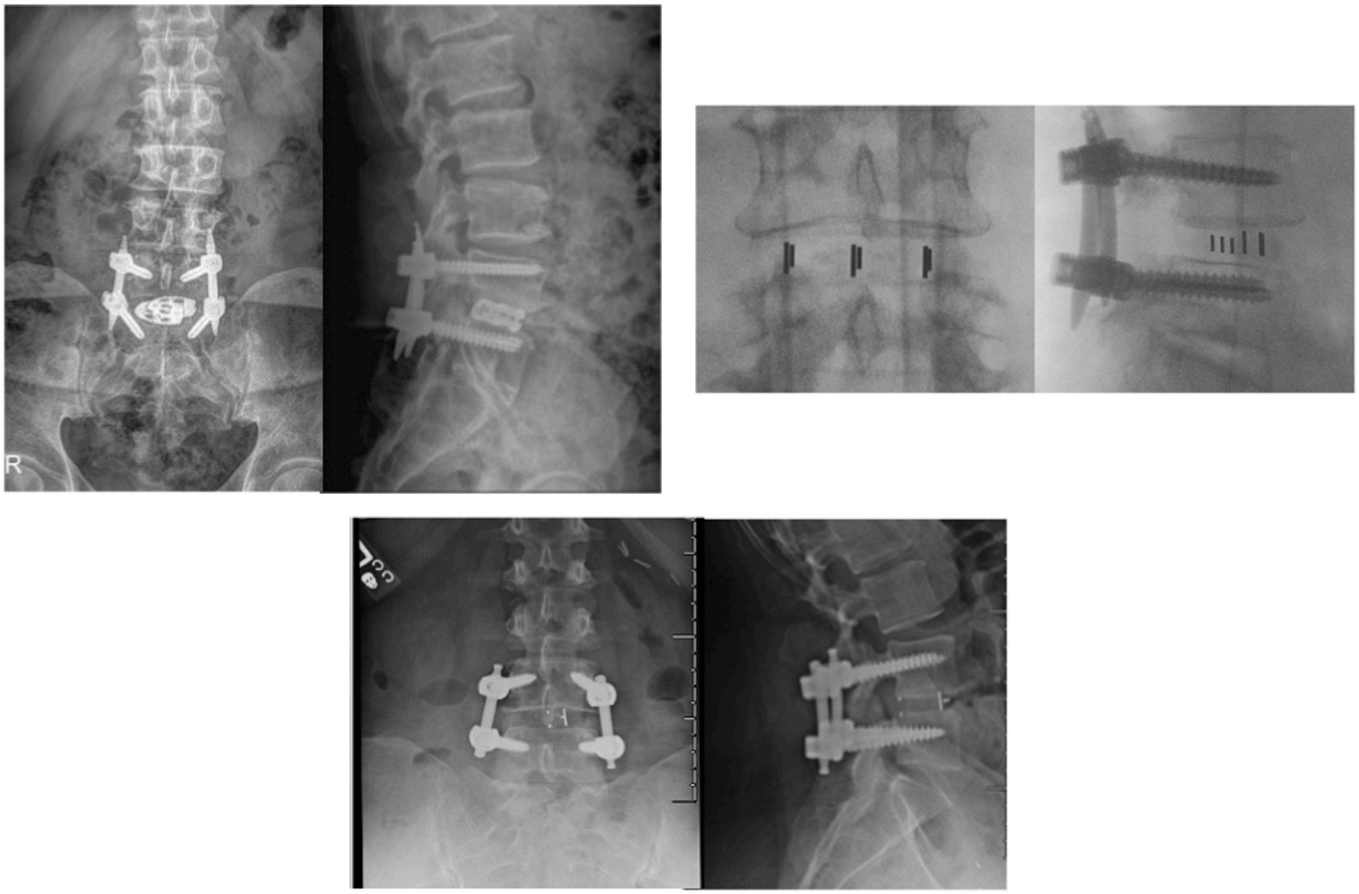

**Fig. 2.** Clinical radiographs of the three strategies used A) two titanium small cages B) Large PEEK cage C) small PEEK cag.

(9.35 ± 2.10 h, 11.97 ± 3.45 h, and 12.28 ± 3.08 h for Groups A, B, and C, respectively).In contrast, the total length of hospital stay showed no significant inter-group difference (8.21 ± 2.73 days, 8.34 ± 2.15 days, and 9.13 ± 3.40 days, respectively($p = 0.321$)(Table 1).

### 3.2. Clinical outcome

All three groups achieved significant and sustained improvement in all patient-reported outcome measures (PROMs) from the preoperative baseline to the final follow-up ($p < 0.05$). The mean ODI score decreased from 61.76 ± 7.31 to 14.56 ± 4.96 in Group A; from 61.25 ± 7.12 to 14.91 ± 6.56 in Group B; and from 64.45 ± 6.06 to 15.58 ± 6.99 in Group C. At the final follow-up, a comparison of ODI scores revealed no statistically significant intergroup difference ($p > 0.05$). The final VAS scores for both leg and back pain were not significantly different among the three groups. All groups demonstrated a marked reduction in Visual Analog Scale (VAS) leg pain scores. The mean scores decreased from 7.35 ± 0.85 (Group A), 7.41 ± 0.84 (Group B), and 7.58 ± 0.90 (Group C) pre-operatively to 1.18 ± 0.52, 1.19 ± 0.78, and 1.35 ± 0.90 respectively, at final follow-up. VAS Back were also improved from 5.91 ± 0.79 (Group A) and 5.97 ± 0.97 (Group B) preoperatively to 1.82 ± 0.72 and 1.84 ± 0.63, respectively, at final follow-up. There were no major complications resulting in a neurological deficit reported in any of the three cohorts (Table 2).

### 3.3. Radiological outcome

Sagittal parameters were evaluated to assess global and segmental balance restoration. All three groups demonstrated improvements in sagittal alignment. Furthermore, there was no statistically significant

**Table 1**
Demographic table.

| Characteristic | Group A (Double Titanium Cage) | Group B (Large PEEK Cage) | Group C (Small PEEK Cage) | *p* value |
|---|---|---|---|---|
| Number of patients | 34 | 32 | 40 | |
| Age (Years) | 69.68 ± 7.36 | 68.59 ± 8.37 | 68.18 ± 9.99 | 0.578 |
| Sex (Male: Female) | 17:17 | 12:20 | 25:15 | 0.476 |
| Follow up (months) | 28.50 ± 2.29 | 42.84 ± 3.04 | 78.00 ± 5.62 | 0.000 |
| BMI (kg/m2) | 25.84 ± 2.85 | 25.98 ± 2.74 | 25.47 ± 2.98 | 0.903 |
| Smoking history | 9/34(26.47%) | 8/32 (25.00%) | 10/40 (25.00%) | 0.605 |
| HTN | 7/34 (20.58%) | 7/32 (21.87%) | 8/40 (20.00%) | 0.595 |
| DM | 9/34 (26.47%) | 8/32 (25.00%) | 10/40 (25.00%) | 0.727 |
| Operative Level | | | | 0.332 |
| L3-4 | 3 | 6 | 4 | |
| L4-5 | 22 | 18 | 20 | |
| L5-S1 | 9 | 8 | 16 | |
| Diagnosis | | | | 0.745 |
| Degenerative Spondylolithesis | 11 | 10 | 12 | |
| Lytic Spondylolithesis | 6 | 4 | 6 | |
| Spinal Stenosis | 8 | 10 | 12 | |
| Central and foraminal stenosis | 9 | 8 | 10 | |
| Primary: Revision | 10:24 | 17:15 | 26:14 | 0.009 |
| Operative Time (Min) | 116.03 ± 11.27 | 138.91 ± 8.59 | 120.88 ± 15.19 | 0.000 |
| Time to Ambulation (Hours) | 9.35 ± 2.10 | 11.97 ± 3.45 | 12.28 ± 3.08 0 | 0.001 |
| Postoperative Length of Stay (Day) | 8.21 ± 2.73 | 8.34 ± 2.15 | 9.13 ± 3.40 | 0.321 |
| Major Complication | 0 | 0 | 0 | |
| Subsidence | 2/34 (5.9%) | 2/32 (6.3%) | 6/40 (15.0%) | 0.035 |

**Table 2**
Clinical outcomes.

| Variables | Group A(Double Titanium Cage) | Group B (Large PEEK Cage) | Group C (Small PEEK Cage) | *p* value |
|---|---|---|---|---|
| VAS (leg) | | | | |
| Preoperative | 7.35 ± 0.85 | 7.41 ± 0.84 | 7.58 ± 0.90 | 0.514 |
| Final | 1.18 ± 0.52 | 1.19 ± 0.78 | 1.35 ± 0.53 | 0.514 |
| VAS (Back) | | | | |
| Preoperative | 5.91 ± 0.79 | 5.97 ± 0.97 | 6.05 ± 1.15 | 0.834 |
| Final | 1.82 ± 0.72 | 1.84 ± 0.63 | 1.80 ± 0.73 | 0.965 |
| ODI | | | | |
| Preoperative | 61.76 ± 7.31 | 61.25 ± 7.12 | 64.45 ± 6.06 | 0.099 |
| Final | 14.56 ± 4.96 | 14.91 ± 6.56 | 15.58 ± 6.99 | 0.777 |

intergroup difference in the degree of correction. Preoperative PT was 17.51 ± 9.58°in Group A,19.39 ± 7.54°in Group B and 20.21 ± 7.63 in Group C. At the final follow-up, the mean change in Pelvic Tilt (ΔPT) was −1.83 ± 5.88°, 0.46 ± 4.06°, and 0.87 ± 4.82° for Groups A, B, and C, respectively ($p = 0.372$). The mean preoperative Lumbar Lordosis (LL) was 40.28 ± 16.16°, 40.40 ± 11.28°, and 39.88 ± 11.90° for Groups A, B, and C, respectively; these baseline values were not significantly different ($p = 0.985$). At the final follow-up, mean LL values improved to 42.01 ± 14.15° (Group A), 42.53 ± 10.39° (Group B), and 42.24 ± 10.72° (Group C), again with no significant intergroup difference ($p = 0.984$).The mean change in LL (ΔLL) was an increase of +1.72 ± 7.05° in Group A, +2.13 ± 6.75° in Group B, and +2.36 ± 7.10° in Group C ($p = 0.927$). The Δ Sacral slope in the three groups also did not show statistically significant results. Mean preoperative Segmental Lordosis (SL) was 10.56 ± 7.12°, 12.81 ± 5.39°, and 12.06 ± 6.31° for Groups A, B, and C, respectively; these baseline values were not significantly different ($p = 0.240$). At the final follow-up, these values increased to 14.07 ± 6.34° (Group A), 13.96 ± 4.85° (Group B), and 14.37 ± 5.12° (Group C). The mean change in SL (ΔSL) was 3.52 ± 6.14° in Group A, +1.15 ± 5.70° in Group B, and +1.59 ± 6.10° in Group C ($p = 0.234$). The change in PI-LL (ΔPI-LL) from preoperative to final was −1.80 ± 7.90° in Group A, −1.85 ± 6.59 in Group B, −2.02 ± 7.38 in Group C ($p = 0.991$). Furthermore, the change in SVA did not differ ($p = 0.897$) (Table 3)

A significant intergroup difference in fusion rates was observed at the 6-month follow-up (97.1% in Group A, 93.7% in Group B, vs. 15.0% in Group C; $p < 0.001$). This significant difference persisted at 12 months, with rates of 100% (Group A), 98.5% (Group B), and 90.0% (Group C) ($p < 0.05$). At the final follow-up, the fusion rates were 100% in Group A, 98.5% in Group B, and 92.5% in Group C. By the final endpoint, the difference among the three groups was no longer statistically significant ($p = 0.845$). No nonunion occurred in Group A, while 1 and 2 cases of nonunion were found in Groups B and C, respectively. The incidence of subsidence (greater than Grade 1 Marchi) was 5.9% (2/34), 6.3% (2/32), and 15.0% (6/40) for Groups A, B, and C, respectively. This difference was statistically significant ($p = 0.035$), with the highest rate observed in Group C, which had a significantly smaller cage surface area.

## 4. Discussion

Transforaminal interbody fusion was originally described by Harms and Jeszensky (12) as a surgical option for a variety of spinal disorders that require a fusion. Compared to the traditional posterior interbody fusion technique (PLIF), the TLIF approach allows for less neural retraction and less neurological injury[14] but with these open techniques, there were significant drawbacks due to their extensive posterior approach, including substantial paraspinal muscle damage, high estimated blood loss, prolonged recovery time, and increased postoperative pain. With the evolution of options, endoscopic means to accomplish TLIF has been reported. With the separation of working and viewing portals, surgeons have more degrees of freedom to accomplish surgery; furthermore, BELIF allows for meticulous disc removal and endplate preparation under direct high power magnification. A challenge with any fusion technique, however, is fusion and in particular interbody fusion, subsidence. In this paper, three different cage options were

**Table 3**
Radiographic outcomes.

| Characteristics | Group A (Double Titanium Cage) | Group B (Large PEEK Cage) | Group C (Small PEEK Cage) | *p* value |
|---|---|---|---|---|
| Preop Lumbar Lordosis (LL) | 40.28 ± 16.16 | 40.40 ± 11.28 | 39.88 ± 11.90 | 0.985 |
| Final LL | 42.01 ± 14.15 | 42.53 ± 10.39 | 42.24 ± 10.72 | 0.984 |
| Δ LL | 1.72 ± 7.05 | 2.13 ± 6.75 | 2.36 ± 7.10 | 0.927 |
| Preop Sacral Slope (SS) | 30.51 ± 8.21 | 31.20 ± 7.21 | 30.80 ± 7.53 | 0.937 |
| Final SS | 29.70 ± 8.23 | 31.48 ± 7.42 | 31.67 ± 7.75 | 0.515 |
| Δ SS | −0.81 ± 4.56 | 0.29 ± 6.93 | 0.86 ± 6.12 | 0.504 |
| Preop PI-LL | 14.32 ± 10.94 | 12.78 ± 8.71 | 13.34 ± 8.94 | 0.809 |
| Final PI-LL | 12.52 ± 8.65 | 11.29 ± 6.88 | 11.73 ± 7.34 | 0.538 |
| Δ PI-LL | −1.80 ± 7.90 | −1.85 ± 6.59 | −2.02 ± 7.38 | 0.991 |
| Preop C7-S1 SVA | 31.22 ± 29.34 | 31.85 ± 25.10 | 36.51 ± 28.16 | 0.722 |
| Final C7-S1 SVA | 25.60 ± 28.86 | 34.89 ± 27.42 | 33.25 ± 25.74 | 0.443 |
| Δ C7-S1 SVA | −5.61 ± 27.25 | 3.05 ± 24.08 | −3.26 ± 24.12 | 0.897 |
| Preop Segmental Lordosis (SL) | 10.56 ± 7.12 | 12.81 ± 5.39 | 12.06 ± 6.31 | 0.240 |
| Final SL | 14.07 ± 6.34 | 13.96 ± 4.85 | 14.37 ± 5.12 | 0.948 |
| Δ SL | 3.52 ± 6.14 | 1.15 ± 5.70 | 1.59 ± 6.10 | 0.234 |
| Preop PT | 17.51 ± 9.58 | 19.39 ± 7.54 | 20.21 ± 7.63 | 0.374 |
| Final PT | 19.34 ± 8.12 | 19.85 ± 6.54 | 20.57 ± 6.46 | 0.937 |
| Δ PT | 1.83 ± 5.88 | 0.46 ± 4.06 | 0.36 ± 4.34 | 0.372 |

analyzed showing a high fusion rate regardless of technique but with less subsidence when using a higher total cage surface area of cage contact.

This current study also adds to the published literature on the safety and efficacy of BELIF. The consistent and favorable clinical results achieved in our cohort, despite the variations in cage strategy, further support BELIF as an effective minimally invasive option. There were significant improvements in patient-reported outcomes (VAS back/leg, ODI) observed across all three cage groups without neurological injury. Other published studies have compared BELIF with traditional techniques. When compared to open PLIF, BELIF had an advantage of reduced early postoperative back pain.[15] Similarly, when compared against minimally invasive tubular TLIF, BETLIF demonstrates comparable long-term functional outcomes and pain relief, while potentially offering faster recovery and less back pain in the immediate postoperative period.[8] Although this study combines variables such as BELIF technique, different number of cages, and different types of cages, the ability to provide safe and reproducible outcomes of BELIF has already been demonstrated. Thus, the variable of technique is minimized, and this study's main goal is compare radiographic and clinical outcomes in different cage utilization strategies.

Although our study cohort included both primary and revision fusion cases, with a statistically significant difference in their distribution among the groups, the final clinical outcomes (VAS scores, ODI) were comparable across all three groups. This observation within our own data suggests that the status of primary versus revision surgery did not lead to substantially different long-term clinical results in this cohort undergoing BELIF. This finding is further supported by a recent publication comparing primary and revision BELIF directly. A study by Kim et al found that while revision BETLIF procedures had significantly longer surgical times and a higher incidence of durotomy compared to primary cases, both groups demonstrated similar clinical improvement in VAS scores, ODI, and MacNab criteria, as well as comparable fusion rates at final follow-up.[16] Therefore, the inclusion of both primary and revision cases in our study is unlikely to have significantly confounded the overall assessment of clinical efficacy. One may question that in a revision setting, the scar tissue in and around the disc space may promote less vascularization for bony fusion potential. Revision cases may also have more sclerosis at the endplates inhibiting healing as well or perhaps because of the scarring, there may be a higher risk of iatrogenic endplate violation during disc preparation. Lastly, revision cases may have scar tissue that tether the neural elements increasing the risk for neuropraxia and worse clinical results. However, this study and the previous study[16] do not support those hypotheses. Furthermore, Group A had a higher percentage of revision cases yet had better radiographic results (less subsidence and quicker fusion rate), opposite of the hypothesis. Nevertheless, we acknowledge that by including both primary and revision cases could add bias to the study. Group A, with more revisions, also had shorter follow up period, but subsidence and radiographic nonunion occur before the second year, and rarely manifest at later time points. Our studies demonstrate fusion rates, specifically did not change much from 1 year follow up to last follow up. Clinical outcomes can deteriorate over time. Yet, iatrogenic injury would manifest at earlier time periods.

The surgical times were longer in the large PEEK cage group than the two smaller cage groups, albeit the average difference was less than 25 min. The reason for this variation was that large PEEK group required more bone work and bleeding control for the insertion of the cage. For smaller cage placement, the entire ipsilateral facet does not need to be removed while in the cases of large case insertion, many times the entire facet has to be removed thoroughly to facilitate cage placement. To help with sagittal alignment, the surgeon attempted to remove the facet to mobilize the motion segment but for larger cage placement, the facetectomy has to be more thorough to place the cage compared to smaller cage techniques as nerve retraction is less likely to help in large cage inertion. Regardless the different in time is likely not clinically significant. The difference in length of stay and time to ambulation were not clinically meaningful. As far as time to ambulation differences, the 3 h difference is likely negligible. Because the surgeries were performed in Asia, the length of stay is drastically different from the United States. The payer system as well as cultural differences prolong length of stay.

With the focus on sagittal alignment in the spinal literature, radiographic alignment parameters were analyzed to assess the restoration and/or maintenance of global and segmental balance. All three groups in this study demonstrated improvements in sagittal alignment; there were no statistically significant differences in the degree of correction among the groups at the final follow-up. Since these cases were all one level in degenerative cases, we did not expect large changes in radiographic parameters, rather hoped for maintenance of a balance spine as all patients did not have a spinal deformity preoperatively. When there is focal lumbar deformity, certain techniques like LLIF or specific cage strategies might improve local and regional lordosis more so than BELIF. Regardless, future studies analyzing these BELIF techniques in spinal deformity patients may be warranted.

For successful lumbar interbody fusion, the interbody cage plays a crucial role in providing structural support until fusion occurs.[17] However, cage subsidence is a common complication that can lead to spinal deformity, neural compression, fusion failure, and the need for revision surgery.[18] Various factors influence cage subsidence, including bone mineral density, endplate preparation, cage size and footprint, cage position (central vs. peripheral), and cage material (PEEK vs. Titanium). Particularly, it has been revealed through several biomechanical studies that the vertebral endplate exhibits regional variations in strength, with the periphery (especially posterolateral) being significantly stronger and stiffer than the central region. Grant et al[17] mapped the strength of the lumbar and sacral endplates, showing that the posterolateral region was more than twice as strong as the central region, and Lowe et al[18] also reported that the posterolateral region had the highest resistance in both the lumbar and thoracic spine, while the central region had the least. These regional strength variations in the endplate provide important implications for cage design and placement strategies. Cage design can also play a factor in structural support. According to the study by Lowe et al, cages with larger diameters (i.e., larger footprints) have a higher maximum load to failure (MLF) and a lower risk of subsidence. Moreover, while hollow cages may have a lower MLF than solid cages of the same diameter, they can withstand higher stress per unit area, indicating potentially higher force transfer efficiency. Thus, hollow cage can achieve similar MLF to smaller solid cages by increasing their diameter. The empty space can also provide an opportunity for placing bone graft. Lastly, since removing the endplate significantly reduces structural strength, the importance of endplate preservation is further emphasized.[12] BELIF allows for careful denuding of the endplate cartilage without endplate violation.

As noted in Mendoza-Lattes's commentary, small-footprint cages and aggressive disc height restoration are associated with endplate injuries and subsidence, highlighting the importance of meticulous surgical technique and precise implant placement aligned with the peripheral vertebral endplates.[12] These biomechanical principles were reflected in the results of our study as well. A statistically significantly higher subsidence rate (15.0%) was observed in Group C (single small PEEK), which had the smallest cage foot print, whereas Groups A (double titanium) and B (single large PEEK), which aimed for a larger effective contact area, had lower subsidence rates of 5.9% and 6.3%, respectively. This suggests that maximizing the area where the cage contacts the stronger peripheral part of the endplate is important for preventing subsidence. Although Group A and B had different material properties, the similarities were the surface area when compared to Group C. If it was only material properties at play, Group B and C would have closer subsidence rates. However, we cannot explicit exclude the possibility of material properties as titanium is stiffer than PEEK. With the advances in 3-D printed titanium, the modulus of elasticity is similar to PEEK. Therefore, in BELIF surgery, securing sufficient contact area and accurately transverse positioning the cage on the strong peripheral region of

the endplate can be considered key factors in increasing fusion success rates and reducing subsidence-related complications.

A notable finding in this study was the significantly higher fusion rates observed in Group A (double titanium cages) and Group B (single large PEEK cage) compared to Group C (single small PEEK cage) at the 6-month and 12-month follow-up time points. Both Group A and Group B utilized cage strategies designed to maximize the effective contact area with the vertebral endplate. This larger footprint likely contributed to enhanced initial stability, a critical factor for successful bone fusion. Biomechanically, distributing load over a wider area, particularly engaging the stronger peripheral apophyseal ring of the endplate, provides greater resistance to subsidence and minimizes micromotion at the graft-endplate interface. Reduced micromotion creates a more favorable environment for osteogenesis and bony bridging.[19] Conversely, the smaller footprint of the cage used in Group C may have concentrated stress on the weaker central endplate region, potentially leading to increased micromotion and the significantly higher rate of subsidence observed (15.0%), which could delay the fusion process. Furthermore, while PEEK (Groups B and C) is considered bioinert, titanium (Group A) possesses osteoconductive properties that can promote direct osteointegration.[20] If material properties were the only important factor, one would surmise Group A to have a higher fusion rate than both Group B and C. Yet, the fusion rates were similar between Group A (titanium) and Group B (PEEK). Therefore, the interplay between surface area and material properties are likely the reasoning rather than just material properties alone for fusion status. Ultimately, the combination of a large surface area engaging the robust peripheral endplate, possibly augmented by the material properties, can perhaps facilitate more rapid and robust early fusion compared to a single, smaller PEEK cage. Perhaps in the future comparing similar cage dimension (large size) but between PEEK and titanium can elucidate the direct effects of material properties.

### 4.1. Limitations

This study has several limitations. First, it follows a retrospective cohort study design. Second, due to varying surgical time points among the patient groups, the follow up duration differed between the groups. Although the final follow up differed, the follow up was at minimum 2 years. Subsidence typically occurs within 6 months of surgery. A longer follow up period would not skew the results to higher subsidence of the longer follow up group. Secondarily, once a patient is fused, longer follow up would not change that fusion rate. One can surmise longer follow up may allow slower fusion to potentially fuse, but fusion rates plateau after 1 year and it is unlikely a substantial fusion rate occurs past 2 years, the minimum follow up period in this cohort. Third, although all surgeries were performed by a single experienced spine surgeon, the operator's learning curve during the study period was not explicitly accounted for. Group C surgical technique was adopted first followed by Group B then A. This learning curve could account for the higher subsidence rate and lower fusion rates as a bias, and a future randomized study would warrant exploration. The surgeon however had a long track record of UBE and has surpassed the learning curve of BELIF but adopting new techniques implicitly has a learning curve. Fourth, the assignment of cage type was not randomized and was based on surgeon preference, and the difference in cage material between Group A (Titanium) and Groups B/C (PEEK) might have influenced the outcomes beyond just the footprint comparison. All cases were performed after the learning curve of BELIF,[21] but Group A and B occurred more recently. Finally, a large titanium cage was not studied or a single small titanium cage. Future prospective randomized controlled trials with larger sample sizes and longer follow-up periods are needed, especially to see if material properties are more important that surface area.

## 5. Conclusion

In this study, biportal endoscopic lumbar interbody fusion (BE-TLIF) using three different cage strategies (double titanium, single large PEEK, single small PEEK) demonstrated satisfactory clinical outcomes with no significant intergroup differences at the final follow-up. However, cage size and material influenced the early fusion rate and the incidence of subsidence. Cages with a larger footprint (Groups A and B) showed faster and superior early fusion rates, while the cage with the smallest footprint (Group C) exhibited a significantly higher rate of subsidence (15.0%). Therefore, appropriate cage size selection is crucial in BELIF, considering that smaller cages may be associated with an increased risk of subsidence.

## CRediT authorship contribution statement

**Ju-Eun Kim:** Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hee Soo Kim:** Writing – review & editing. **Daniel K. Park:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Daniel park reports a relationship with Stryker that includes: consulting or advisory. Daniel park reports a relationship with GetSet that includes: consulting or advisory. Daniel park reports a relationship with Arthrex Inc that includes: consulting or advisory. Daniel park reports a relationship with Orthofix Medical Inc that includes: funding grants. Daniel park reports a relationship with Medynus that includes: consulting or advisory. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References


1. de Kunder SL, van Kuijk SM, Rijkers K, et al. Transforaminal lumbar interbody fusion (TLIF) versus posterior lumbar interbody fusion (PLIF) in lumbar spondylolisthesis: a systematic review and meta-analysis. *Spine J*. 2017;17(11):1712–1721.
2. Kawaguchi Y, Matsui H, Tsuji H. Back muscle injury after posterior lumbar spine surgery. A histologic and enzymatic analysis. *Spine*. 1996;21(8):941–944.
3. Kang MS, You K, Choi J, et al. Minimally invasive transforaminal lumbar interbody fusion using the biportal endoscopic techniques versus microscopic tubular technique. *Spine J*. 2021;21(12):2066–2077.
4. Foley KT, Lefkowitz MA. Advances in minimally invasive spine surgery. *Clin Neurosurg*. 2002;49:499–517.
5. Cheng JS, Park P, Le H, et al. Short-term and long-term outcomes of minimally invasive and open transforaminal lumbar interbody fusions: is there a difference? *Neurosurg Focus*. 2013;35(2):E6.
6. Kim JE, Choi D, Park EJ, et al. Biportal endoscopic spinal surgery for lumbar spinal stenosis. *Asian Spine J*. 2019;13(2):334–342.
7. Park SM, Kim H, Kim G, et al. Learning curve for lumbar decompressive laminectomy in biportal endoscopic spinal surgery using the cumulative summation test for learning curve. *World Neurosurg*. 2019;122:e1007–e1013.
8. Kim JE, Yoo H, Choi D, et al. Comparison of minimal invasive versus biportal endoscopic transforaminal lumbar interbody fusion for single-level lumbar disease. *Clin Spine Surg*. 2021;34(2):E64–E71.
9. Min WK, Kim J, Choi D, et al. Clinical and radiological outcomes between biportal endoscopic decompression and microscopic decompression in lumbar spinal stenosis. *J Orthop Sci*. 2020;25(3):371–378.
10. Teng I, Han J, Phan K, et al. A meta-analysis comparing ALIF, PLIF, TLIF and LLIF. *J Clin Neurosci*. 2017;44:11–17.
11. You KH, Cho SK, Hwang J, et al. Effect of cage material and size on fusion rate and subsidence following biportal endoscopic transforaminal lumbar interbody fusion. *Neurospine*. 2024;21(3):973–983.
12. Mendoza-Lattes SA. CORR Insights(R): poor bone quality, multilevel surgery, and narrow and tall cages are associated with intraoperative endplate injuries and late-onset cage subsidence in lateral Lumbar interbody fusion: a systematic review. *Clin Orthop Relat Res*. 2022;480(1):189–190.
13. Harms J, Jeszenszky D. The unilateral transforaminal approach for posterior lumbar interbody fusion. *Orthop Traumatol*. 1998;6:88–99.

14. Cole CD, McCall TD, Schmidt MH, et al. Comparison of low back fusion techniques: transforaminal lumbar interbody fusion (TLIF) or posterior lumbar interbody fusion (PLIF) approaches. *Curr Rev Musculoskelet Med*. 2009;2(2):118–126.
15. Park MK, Park D, Son S, et al. Clinical and radiological outcomes of unilateral biportal endoscopic lumbar interbody fusion (ULIF) compared with conventional posterior lumbar interbody fusion (PLIF): 1-year follow-up. *Neurosurg Rev*. 2019;42(3):753–761.
16. Kim JE, Park EJ, Park DK. Biportal endoscopic transforaminal interbody fusion: comparing primary versus revision cases. *J Am Acad Orthop Surg*. 2024;33(18):e1081–e1091.
17. Grant JP, Oxland TR, Dvorak MF. Mapping the structural properties of the lumbosacral vertebral endplates. *Spine*. 2001;26(8):889–896.
18. Lowe TG, Hashim S, Wilson LA, et al. A biomechanical study of regional endplate strength and cage morphology as it relates to structural interbody support. *Spine*. 2004;29(21):2389–2394.
19. Oxland TR, Grant JP, Dvorak MF, et al. Effects of endplate removal on the structural properties of the lower lumbar vertebral bodies. *Spine*. 2003;28(8):771–777.
20. Campbell PG, Cavanaugh DA, Nunley P, et al. PEEK versus titanium cages in lateral lumbar interbody fusion: a comparative analysis of subsidence. *Neurosurg Focus*. 2020;49(3):E10.
21. Kim JE, Yoo H, Choi D, et al. Learning curve and clinical outcome of biportal endoscopic-assisted lumbar interbody fusion. *Biomed Res Int*. 2020;2020, 8815432.