Sagittal Alignment and Clinical Outcomes After Biportal Endoscopic Transforaminal Lumbar Interbody Fusion Using a Single Expandable Cage: One Year Follow-up

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■ OBJECTIVE: **Advancements in expandable cage technology may overcome limitations, such as narrow working corridor, continuous irrigation, and endplate injury risk in biportal endoscopic transforaminal lumbar interbody fusion (BE-TLIF). We evaluate sagittal realignment, fusion rates, and clinical outcomes over 1 year using a single bullet-type expandable cage.**

■ METHODS: **This retrospective study included 29 patients (38 levels) who underwent BE-TLIF with a single expandable cage and were followed for at least 12 months. Radiological assessments included disc height (DH), segmental lordosis (SL), lumbar lordosis (LL), pelvic incidence (PI), pelvic tilt (PT), PI—LL mismatch, and cage subsidence. Clinical outcomes were evaluated using back and leg Visual Analog Scale (VAS), Oswestry Disability Index (ODI), 36-Item Short Form Survey (SF-36), and EuroQol-5 Dimension (EQ-5D). Fusion was evaluated using CT based Bridwell classification at 6 and 12 months.**

■ RESULTS: **At 12 months, the fusion rate was 92.1%, with significant subsidence (≥2 mm) in 3 levels. Anterior and posterior DH increased by 3.97 and 4.22 mm, while SL and LL improved by 3.01° and 5.00°, respectively. Back and leg VAS and ODI decreased by 3.0, 5.0, and 12.76 points, while EQ-5D increased by 5.81 points. Greater PI—LL correction correlated with higher fusion rates and better functional recovery. Patients with preoperative sagittal malalignment showed significant improvements. Cage size and type had limited effect on outcomes.**

■ CONCLUSIONS: **BE-TLIF using a single bullet-type expandable cage achieved favorable outcomes at 1 year, with meaningful sagittal correction and fusion rates, supporting the non-inferiority of this construct in short-segment lumbar fusion.**

INTRODUCTION

Biportal endoscopic transforaminal lumbar interbody fusion (BE-TLIF) has emerged as a viable and minimally invasive surgical method for the treatment of degenerative lumbar diseases, offering direct and indirect neural decompression with reduced posterior structure injuries.[1]

Key words
- Biportal endoscopic spine surgery
- Biportal endoscopic transforaminal interbody fusion
- expandable cage
- sagittal alignment
- Interbody fusion

Abbreviations and Acronyms
ALIF: Anterior lumbar interbody fusion
BE-TLIF: Biportal endoscopic transforaminal lumbar interbody fusion
BMD: Bone mineral density
DH: Disc height
EBL: Estimated blood loss
EQ-5D: EuroQol-5 Dimension
HA: Hydroxyapatite
HOD: Hospital stays
LL: Lumbar lordosis
ODI: Oswestry disability index
OLIF: Oblique lumbar interbody fusion
PEEK: polyetheretherketone
PI: Pelvic incidence
PI-LL mismatch: Pelvic incidence—lumbar lordosis mismatch
PT: Pelvic tilt
rh-BMP2: Recombinant human bone morphogenetic protein-2
SF-36: 36-Item Short Form Survey
SL: Segmental lordosis
VAS: Visual analog scale

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Citation: World Neurosurg. (2026) 205:124698. http://doi.org/10.1016/j.wneu.2025.124698

*Journal homepage: **www.journals.elsevier.com/world-neurosurgery***

*Available online: **www.sciencedirect.com***

Compared with traditional open or tubular minimally invasive approaches, BE-TLIF provides a wider working field and precise visualization through independent viewing and working portals, allowing more meticulous endplate preparation.[2,3]

However, the risk of age-related complications, such as subsidence, cage loosening, or nonunion—particularly when narrow cages are used that may not withstand focal endplate pressure—remains an area of ongoing debate. Consequently, several studies have emphasized that larger-footprint or dual-cage constructs provide a broader contact area with the apophyseal ring, thereby reducing subsidence risk.[4-6] Nevertheless, the insertion of such cages can be technically challenging in endoscopic procedures because of the narrow working corridor, potential endplate injury, and the increased risk of neural traction. In particular, whether satisfactory biomechanical stability can be achieved using a single cage construct remains uncertain, as the limited footprint theoretically increases the risk of inadequate load distribution, subsidence, and insufficient lordotic restoration.

In addition to cage size and design, spinopelvic parameters used to assess sagittal alignment have become key predictors of postoperative outcomes in lumbar fusion surgery. Restoration of sagittal alignment is now considered crucial even in short-level fusion procedures. Parameters such as disk height (DH), segmental lordosis (SL), pelvic tilt (PT), lumbar lordosis (LL), and the mismatch between pelvic incidence (PI) and LL (PI—LL mismatch) are increasingly recognized as essential determinants of both radiographic and clinical outcomes.[7,8]

Furthermore, the osteoinductive potential of recombinant human bone morphogenetic protein-2 (rh-BMP2) may enhance early biological stability and compensate for the inherent footprint limitations of single-cage constructs, although its clinical effectiveness specifically within the BE-TLIF environment has not been well established.

Therefore, this study aimed to evaluate whether BE-TLIF using a single bullet-type expandable cage could achieve satisfactory clinical outcomes and fusion rates, while also providing adequate correction of sagittal alignment, over a minimum follow-up period of 1 year.

MATERIAL AND METHODS

Patient Selection

This retrospective study was approved by the Institutional Review Board and included 75 patients who underwent BE-TLIF at our institution between March 2023 and June 2024. All procedures were performed by a single spine surgeon with experience in more than 100 cases of endoscopic fusion, using an identical surgical protocol. During this period, the inclusion criteria were as follows: (1) single or two-level BE-TLIF was performed in adult patients (aged ≥19 years); (2) diagnosis of lumbar degenerative disease with foraminal stenosis, including spinal stenosis, spondylolisthesis, or degenerative disc disease; and (3) persistent back or leg pain refractory to conservative treatment for more than 3 months. The exclusion criteria were as follows: (1) history of prior surgery at the index level, (2) presence of systemic inflammatory conditions (e.g., rheumatoid arthritis, pneumonia, dermatitis, or bronchitis), (3) radiologic findings limited to mild foraminal stenosis or isolated central canal stenosis, (4) neurologic symptoms attributed to non-spinal etiologies such as vascular disorders, and (5) incomplete follow-up data, defined as a follow-up period of less than 12 months or the absence of either imaging studies or clinical outcome assessments during follow-up. Ultimately, 29 of the 75 patients at 38 operative levels were included in the analysis.

Surgical Procedure

All procedures were performed under general anesthesia, with the patient in the prone position on a radiolucent operating table. BE-TLIF was performed using the unilateral approach for cage insertion. We used a single-peak-type titanium expandable cage (Excander TLIF cage system; CG Bio, South Korea) with a width of 11 mm. This implant is available in 2 lengths: 28 and 32 mm. The cage was offered with fixed lordotic angles of 12° or 20° (convex or hyperlordotic type), with an initial height of 8 or 10 mm, and was expandable up to 4 mm via a torque driver capable of withstanding 2.5 N (N). After the final cage insertion, additional bone graft material was delivered through a dedicated posterior injection channel.

Two vertical incisions, each approximately 1 cm in length, were made near the lateral border of the pedicle at the target level, and were used as the working and viewing portals. This incision technique offers several advantages. First, percutaneous pedicle screws can be inserted through the same incisions without additional skin incisions. Second, if needed, both central and contralateral side decompression can be performed through the same portals. Following blunt dissection using a muscle detacher, the bony structures, including the facet joint and interlaminar space, were adequately exposed. Central and contralateral foraminal decompression were performed following standard endoscopic decompression techniques when indicated.[9] For ipsilateral facetectomy, the facet capsule was ablated using a radiofrequency ablator (RF ablator) to clearly visualize the lateral margin of the facet joint and identify the inferior articular process (IAP) and superior articular process (SAP). Facetectomy was then carried out using an osteotome, ensuring preservation of the pedicle by maintaining a safe resection margin. The resected bone was harvested and used as autologous bone graft material. After removal of the foraminal ligamentum flavum (LF), lateral margin of the dural sac, exiting nerve root, traversing nerve root, and disc space were clearly visualized. Annulotomy and endplate preparation were then performed using disc reamers. A key advantage of the BE-TLIF technique is the use of a 30° endoscope, which provides excellent visualization of the disc space and allows for complete removal of disc material and cartilage, including contralateral disc preparation. This procedure enables more effective endplate cleaning, which is essential for successful interbody fusion. After sequential trials under C-arm fluoroscopic guidance, an expandable cage trial was inserted and expanded to determine the appropriate size and angle of the final cage. A specialized endoscopic funnel was then insert into the disc space for bone graft. Irrigation was temporarily stopped, and the residual fluid was cleared in surgical field to allow for bone graft insertion, after which the final cage was placed. After cage expansion, a specialized funnel is attached to allow the insertion of 1.5 cc of a product (Novosis; CG bio, South Korea) consisting of a mixture of 1.0 cc rh-BMP2 and 0.5 cc hydroxyapatite (HA), which is then delivered into the expanded space. Percutaneous pedicle screws were inserted and

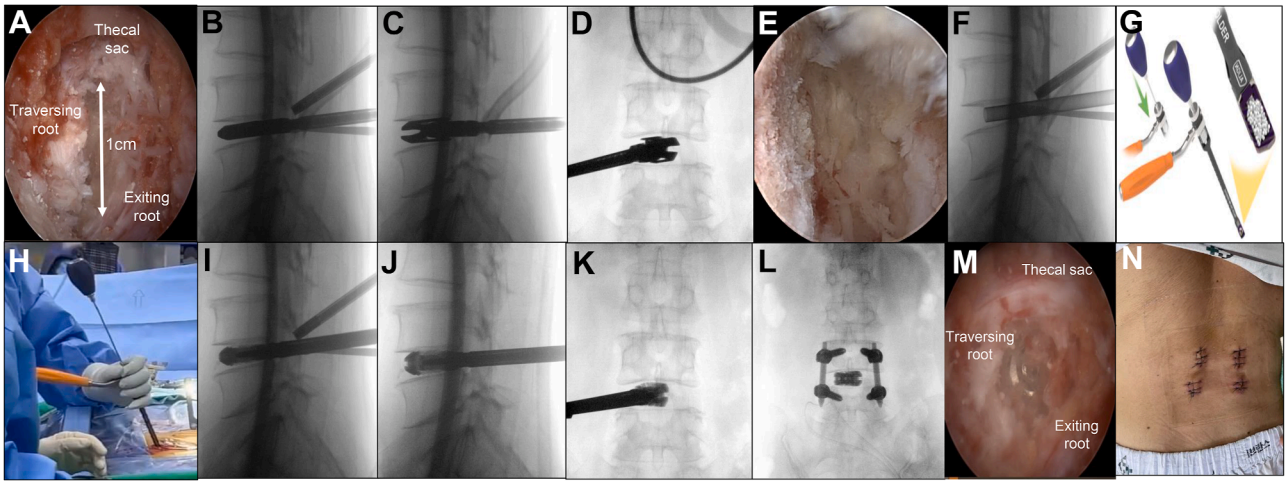

Figure 1. Overview of the BE-TLIF procedure using a single expandable cage (**A**) Following total facetectomy and removal of the foraminal ligament, sufficient space for disc preparation becomes available. (**B**–**D**) Using cage trials, the appropriate size and type of cage are selected, and the optimal cage position is confirmed. (**E**) Disc space preparation is verified using a 30° endoscope. (**F**) Bone graft is inserted through a specialized funnel after temporarily stopping irrigation. (**G**, **H**) 1.5 cc of Rh-BMP2 with HA is inserted with specialized funnel after cage expansion. (**I**–**L**) Actual cage insertion and screw fixation steps are performed. (**M**) The expandable cage is shown in its final, optimal position. (**N**) Postoperative image of the surgical wounds shows only 4 small skin incisions, each approximately 1 cm in length.

posterior instrumentation was completed using appropriately contoured rods (Figure 1).

During interbody cage insertion, meticulous protection of the exiting nerve root, traversing nerve root, and dural sac is essential. Therefore, continuous endoscopic visualization of the disc space is mandatory throughout this step. If additional working space is required, partial resection of the lamina or the superior articular process (SAP) may be performed, and a nerve root retractor may be utilized as necessary. Due to the natural curvature of the lumbar spine, especially at lower lumbar levels, inserting the cage from the right side is generally preferred, as it reduces the risk of endplate damage and avoids the need for additional incisions. However, in cases where access from the right is not feasible—such as when approaching from the left side or in anatomically difficult situations—an additional incision may be required for safe cage placement.

Outcome Evaluation

We analyzed perioperative parameters, including operative time, estimated blood loss (EBL), and length of hospital stay (HOD). Immediate postoperative computed tomography (CT) and X-ray images were used to evaluate the cage position and contact surface. Radiological parameters were independently measured by 3 spine surgeons from the same institution, and the mean values of their measurements were used for analysis. Cage positioning was evaluated using 2 complementary methods to provide both categorical and quantitative assessments. First, the position of the cage was classified according to the location of the tip of the bullet-type cage within the disc space—categorized as ipsilateral, middle, or contralateral relative to the insertion side. Second, axial CT scans were analyzed using a 3 × 3 grid–based mapping system, in which a uniform 3 × 3 grid was superimposed onto the vertebral body at the mid-disc level, dividing the endplate into 9 equal regions. The cage contact surface was calculated as the median ratio of the cage contact area to the total cross-sectional area of the upper and lower endplates (ZETTA PACS viewer system, TY Soft, Korea) (Figure 2). All radiologic parameters,

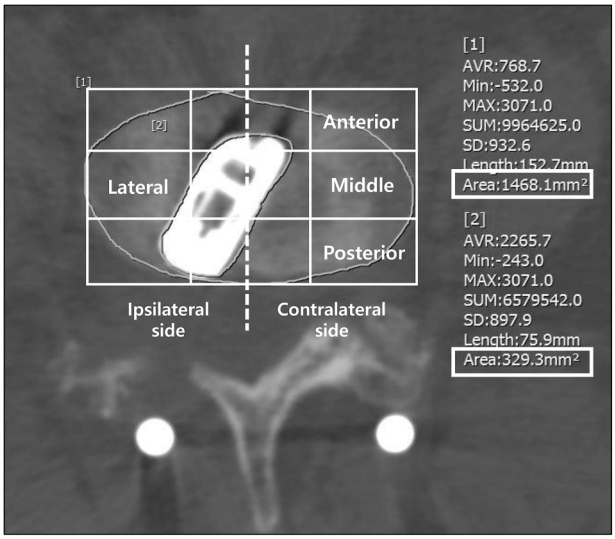

Figure 2. Measurement of cage-endplate contact surface and position of cage assessed using 3 × 3 grid system. The contact areas between the cage and the upper and lower endplates were automatically calculated using region of interest (ROI) analysis on CT axial images. Also, the vertebral body on axial CT image was divided into 9 segments, and the area covered by the interbody cage was determined.

including disc height, segmental lordosis, lumbar lordosis, and cage subsidence, were independently measured by 2 fellowship-trained spine surgeons who were blinded to each other's assessments. To assess reproducibility and inter-observer reliability, the intra-class correlation coefficient (ICC) was calculated using a two-way random-effects model with absolute agreement. The overall inter-observer reliability demonstrated good to excellent agreement, with an ICC of 0.88 (95% CI: 0.81–0.93). According to established criteria, ICC values < 0.50 indicate poor reliability, 0.50–0.75 moderate, 0.75–0.90 good, and >0.90 excellent reliability.

Clinical outcomes were evaluated preoperatively and at 12 months postoperatively using the Back Visual Analog Scale (VAS), Leg VAS, Oswestry Disability Index (ODI), 36-Item Short Form Survey (SF-36), and EuroQol-5 Dimension (EQ-5D). The MCID thresholds for each clinical outcome were defined based on established literature for lumbar fusion surgery: back VAS 1.2, leg VAS 1.6, ODI 12.8, SF-36 4.9 and EQ-5D 0.19.[10,11]

Radiographic outcomes at the same time points included the anterior disc height (anterior DL), posterior disc height (posterior DL), disc wedge angle, segmental lordosis (SL), and lumbar lordosis (LL) as measured on plain radiographs. The EOS imaging system (EOS Imaging, Paris, France) was used to assess the pelvic incidence (PI) and pelvic tilt (PT), and the degree of PI–LL mismatch was calculated to evaluate changes in sagittal alignment more precisely. Malalignment in sagittal parameters was defined as follows: LL < 40° or >60°, PT < 10° or >20°, and PI–LL mismatch beyond −10° to +10° (Figure 3). Additionally, CT scans at 6 and 12 months postoperatively were used to confirm the degree of fusion based on the Bridwell classification: Grade I, complete fusion with remodeling; Grade II, intact graft with no radiolucency; Grade III, intact graft with lucency; and Grade IV, no fusion with lucency. Cage subsidence or migration was also assessed. Significant cage subsidence was defined as cage invasion into the vertebral body exceeding 2 mm and was assessed based on disc height measurements (Figure 4).

Statistical Analysis

We assessed the normality of each variable using the Shapiro–Wilk test. Based on the results of the normality test, parametric or non-parametric statistical methods were applied accordingly. Fusion rates were analyzed using Fisher's exact test for categorical variables, continuous variables were analyzed using the independent two-sample t-test for parametric data and the Mann–Whitney U test for non-parametric data. Comparisons between preoperative and postoperative values, the paired t-test was used for parametric variables, and the Wilcoxon signed-rank test was used for non-parametric variables. All statistical analyses were conducted using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA), and a P-value of <0.05 was considered statistically significant.

RESULTS

Demographic Data

Among the 29 patients included in this study, 5 were male and 24 were female, with a mean age of 72.11 years (range, 52–89 years). The mean BMD was −1.9 (range, −0.1- −2.8), and the mean BMI was 25.1 (range 19.2–30.4). A total of 20 patients underwent single-level fusion, and 9 underwent two-level fusion, resulting in 38 fused levels overall. The average HOD was 8.97 days (range, 6–30 days), and the mean follow-up duration was 16.9 months (range, 14–24 months). Regarding fusion rate and subsidence incidence, a statistically significant difference was observed in the postoperative 6 months fusion rate according to the level of cage insertion; however, no significant differences were found at the postoperative 12 months follow-up period. Other demographic

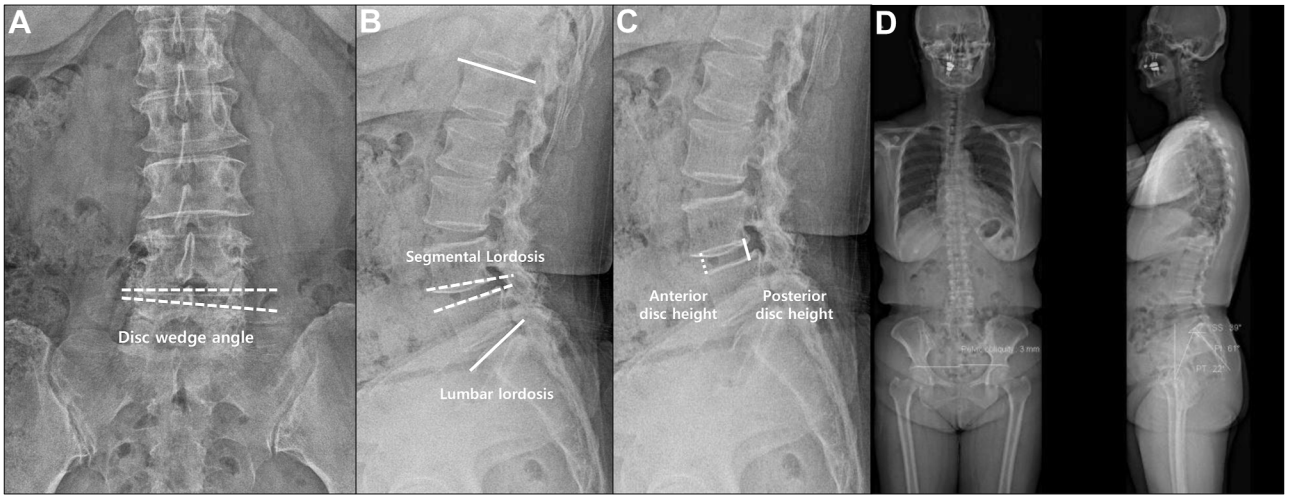

Figure 3. Measurement of radiological parameters (**A**–**C**) Disc wedge angle, segmental lordosis, lumbar lordosis, anterior disc height and posterior disc height were measured in standing X-ray. (**D**) Pelvic incidence and pelvic tilt were calculated in EOS imaging.

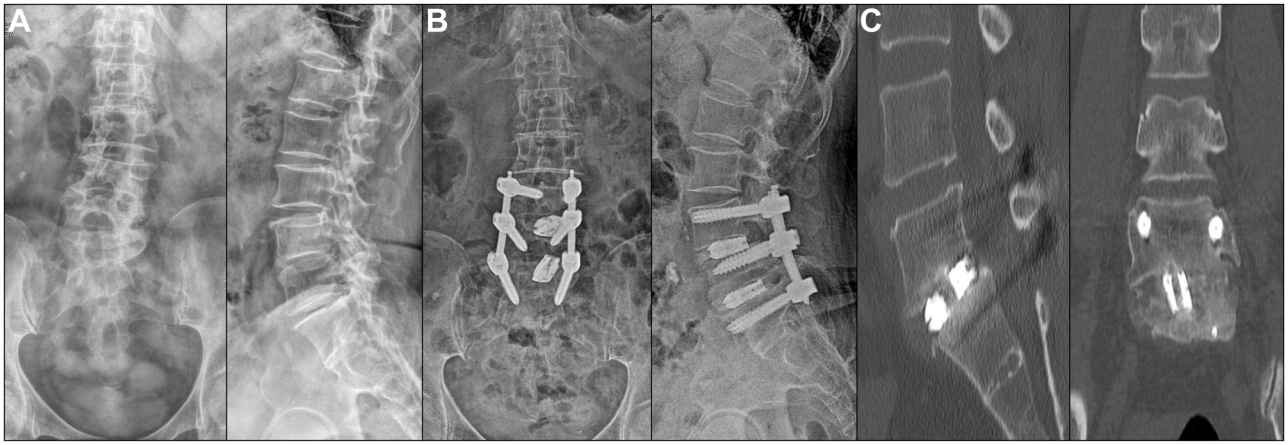

Figure 4. Measurement of cage subsidence and fusion grade (**A**, **B**) Preoperative and postoperative standing radiographs were reviewed during follow up period to confirm cage subsidence or migration. (**C**) Fusion grade was evaluated on CT at 6 and 12 months postoperatively based on bony bridge or lucency.

variables were not significantly associated with fusion rate or subsidence incidence (Table 1).

Fusion Rate and Subsidence Incidence with Complications

At 6 months postoperatively, the fusion rate—defined as Bridwell grade I or II—was 55.26% (21 levels). At 12 months, fusion rate increased to 92.11% (35 levels). A total of 11 levels showed subsidence during follow-up period: 5 levels at 2 months, 4 levels at 3 months, and 2 levels at 4 months postoperatively. Among these, significant subsidence (≥2 mm) was observed in 3 levels (range, 2.3–3.5 mm). Endplate injury was identified intraoperatively at 2 levels in significant subsidence cases, both of which showed a subsidence of 2.5 mm within 2 months postoperatively. Of these, one level showed failed to achieve fusion at the 12 months postoperatively. Also, another one level in significant subsidence cases failed to achieve fusion at 12 months, and posterior cage migration of 5 mm was noted at 6 months postoperatively. Nevertheless, none of the operated patients demonstrated progressive screw loosening or cage migration that resulted in clinical problems during the follow-up period.

However, the patient remained asymptomatic without neurological deficits or significant back pain and has been followed on an outpatient clinic. There were no other complications related to the surgery such as dura tear, hematoma or cage-related issues were observed. Although detailed serological parameters were not included in the primary analysis due to the single-arm study design, routine postoperative laboratory evaluations demonstrated no clinically significant anemia requiring transfusion, no elevation of muscle injury markers indicative of severe muscle damage, and no laboratory evidence suggestive of postoperative infection.

Analysis of cage-related parameters such as cage size, type, location, and position revealed no statistically significant associations with either fusion or subsidence rates. The average endplate contact area of the single bullet-type expandable cage was 19.13%, which was also not statistically associated with fusion outcomes (Table 1).

Radiological and Clinical Outcomes

At 12 months postoperatively, X-ray showed a mean increase in anterior DH of 3.97 mm and posterior DH of 4.22 mm. SL improved by an average of 3.01°, while LL increased by 5.00°. Disc wedge angle and PT changed by approximately −1°, and the PI-LL mismatch improved by 4.00° on average. Except for PT, all radiological parameters demonstrated statistically significant improvements. In terms of clinical outcomes, back VAS improved by an average of 3 points, leg VAS by 5 points, ODI by 12.76 points, and EQ-5D by 5.81 points. SF-36 scores showed mean improvements of 12.88 in the physical component and 14.50 in the mental component. All clinical parameters showed statistically significant improvements (Table 2). Higher degrees of anterior DH restoration and correction of SL and LL were associated with increased fusion rates and decreased incidence of subsidence. Greater improvement in PI-LL mismatch was significantly associated with higher fusion rates. Moreover, at 12 months postoperatively, patients in the fusion group showed significantly greater improvement in back VAS, leg VAS, SF-36 mental component, and EQ-5D scores. ODI and SF-36 physical component also relatively improved more in the fusion group (Table 1). The mean difference in ODI improvement was 12.55% (95% CI: 10.59–14.51), which approached the MCID threshold of 12.8 (0.98 times the MCID; $P < 0.001$). This relatively lower ODI improvement compared with other PROs may be attributed to the lower baseline ODI scores in our cohort, as patients presented with less severe preoperative disability. The mean differences in the VAS for leg pain and back pain were 4.76 (95% CI, 4.36–5.16) and 3.45 (95% CI, 2.75–4.15), corresponding to approximately 3 times and nearly 3 times the MCID values of 1.6 and 1.2, respectively (both $P < 0.001$). SF-36 improved by 12.70 (95% CI: 10.62–14.78), more than twice the MCID of 4.9 ($P < 0.001$).

Table 1. Fusion Rate and Subsidence Incidence

		Fusion Grade (6 months)			Fusion Grade (12 months)			Subsidence		
		Non-fusion (n = 17)	Fusion (n = 21)	*P*-Value	Non-fusion (n = 3)	Fusion (n = 35)	*P*-Value	No (n = 27)	Yes (n = 11)	*P*-Value
Variable	**Total**	**n (%) or Mean ± SD/Median (Q1-Q3)**								
Demographic data										
Age (years)	72.11 ± 8.29	74.59 ± 6.65	70.10 ± 9.08	0.097	74.67 ± 3.21	71.89 ± 8.58	0.584	70.85 ± 8.31	75.18 ± 7.77	0.147
Sex				0.709			>0.999			0.395
Male	8 (21.1)	3 (17.6)	5 (23.8)		0 (0.0)	8 (22.9)		7 (25.9)	1 (9.1)	
Female	30 (78.9)	14 (82.4)	16 (76.2)		3 (100.0)	27 (77.1)		20 (74.1)	10 (90.9)	
BMI (kg/m^2)	25.08 ± 2.72	24.48 ± 2.99	25.56 ± 2.43	0.225	23.88 ± 4.93	25.18 ± 2.54	0.434	25.10 ± 2.36	25.01 ± 3.58	0.926
BMD	−2.3 (−2.8 to −1.3)	−2.2 (−2.5 to −1.4)	−2.3 (−2.8 to −1.3)	0.659	−1.4 (−3.4 to0.2)	−2.3 (−2.8 to −1.3)	0.724	−2.3 (−2.8 to −1.3)	−2.1 (−2.8 to −1.3)	0.834
Operation time (min)	255.0 (215.0–330.0)	290.0 (220.0–355.0)	250.0 (215.0–290.0)	0.445	330.0 (260.0–370.0)	250.0 (210.0–330.0)	0.203	250.0 (215.0–300.0)	290.0 (200.0–365.0)	0.478
EBL (mL)	177.5 (105.0–300.0)	145.0 (105.0–225.0)	200.0 (140.0–310.0)	0.347	160.0 (145.0–410.0)	195.0 (105.0–300.0)	0.498	200.0 (110.0–310.0)	150.0 (100.0–225.0)	0.266
HOD (days)	8.97 ± 4.48	9.82 ± 6.16	7.62 ± 2.13	0.175	17.33 ± 11.59	7.86 ± 2.58	0.292	8.37 ± 1.86	12.64 ± 7.15	0.078
ASA classification				0.067			0.234			0.335
1	2 (5.3)	0 (0.0)	2 (9.5)		0 (0.0)	2 (5.7)		2 (7.4)	0 (0.0)	
2	19 (50.0)	6 (35.3)	13 (61.9)		0 (0.0)	19 (54.3)		15 (55.6)	4 (36.4)	
3	17 (44.7)	11 (64.7)	6 (28.6)		3 (100.0)	14 (40.0)		10 (37.0)	7 (63.6)	
Level				**0.005***			0.407			0.159
L2-3	2 (5.3)	1 (5.9)	1 (4.8)		0 (0.0)	2 (5.7)		1 (3.7)	1 (9.1)	
L3-4	3 (7.9)	2 (11.8)	1 (4.8)		1 (33.3)	2 (5.7)		1 (3.7)	2 (18.2)	
L4-5	18 (47.4)	12 (70.6)	6 (28.6)		1 (33.3)	17 (48.6)		12 (44.4)	6 (54.5)	
L5-S1	15 (39.5)	2 (11.8)	13 (61.9)		1 (33.3)	14 (40.0)		13 (48.1)	2 (18.2)	
Cage related data										
Cage size				0.744			>0.999			0.721
28 mm	19 (50.0)	9 (52.9)	10 (47.6)		2 (66.7)	17 (48.6)		13 (48.1)	6 (54.5)	
32 mm	19 (50.0)	8 (47.1)	11 (52.4)		1 (33.3)	18 (51.4)		14 (51.9)	5 (45.5)	
Cage type				0.847			0.55			0.285
Convex	23 (60.5)	10 (58.8)	13 (61.9)		1 (33.3)	22 (62.9)		18 (66.7)	5 (45.5)	
Hyper-lordotic	15 (39.5)	7 (41.2)	8 (38.1)		2 (66.7)	13 (37.1)		9 (33.3)	6 (54.5)	

Cage location				>0.999			0.403			0.894
Contralateral	20 (52.6)	9 (52.9)	11 (52.4)		2 (66.7)	18 (51.4)		15 (55.6)	5 (45.5)	
Ipsilateral	6 (15.8)	3 (17.6)	3 (14.3)		1 (33.3)	5 (14.3)		4 (14.8)	2 (18.2)	
Middle	12 (31.6)	5 (29.4)	7 (33.3)		0 (0.0)	12 (34.3)		8 (29.6)	4 (36.4)	
Cage position (%)				0.217			0.645			0.384
Anterior	32 (84.2)	14 (36.8)	18 (47.4)		1 (33.3)	31 (88.6)		26 (96.3)	6 (54.5)	
Middle	38 (100)	17 (44.7)	21 (55.3)		3 (100)	35 (100)		27 (100)	11 (100)	
Posterior	35 (92.1)	17 (44.7)	18 (47.4)		2 (66.7)	33 (94.3)		25 (92.6)	10 (90.9)	
Lateral	20 (52.6)	11 (28.9)	9 (23.7)		2 (66.7)	18 (51.5)		14 (51.9)	6 (54.5)	
Cage contact surface (%)	19.13 ± 2.59	18.87 ± 2.98	19.34 ± 2.29	0.582	18.61 ± 2.85	19.17 ± 2.61	0.723	18.78 ± 2.78	19.98 ± 1.91	0.201
Radiological outcome (Difference between preoperative and postoperative 6 or 12 months data)										
Anterior DH (mm)	3.97 ± 2.66	2.95 ± 2.76	4.79 ± 2.33	**0.032***	−1.53 ± 2.23	4.44 ± 2.13	**<0.001***	4.66 ± 2.20	2.27 ± 3.02	**0.01***
Posterior DH (mm)	4.22 ± 1.45	3.79 ± 1.45	4.57 ± 1.39	0.1	3.03 ± 2.80	4.32 ± 1.30	0.51	4.46 ± 1.41	3.63 ± 1.44	0.11
SL (degree)	3.01 ± 3.19	1.79 ± 3.04	3.99 ± 3.03	**0.033***	−2.70 ± 1.61	3.49 ± 2.79	**<0.001***	4.01 ± 2.82	0.55 ± 2.74	**0.001***
LL (degree)	5.0 (3.0—9.0)	4.0 (−2.0 to 7.0)	7.0 (4.0—9.0)	0.085	−9.0 (−13.0 to −2.0)	6.0 (4.0—9.0)	**0.011***	7.0 (4.0—10.0)	4.0 (−2.0 to 6.0)	**0.049***
Disc wedge angle (degree)	−1.0 (−2.7 to −0.1)	−1.4 (−3.4 to −0.3)	−0.4 (−2.1 to −0.1)	0.223	−0.2 (−8.5 to 0.0)	−1.1 (−2.7 to −0.1)	0.935	−0.8 (−2.7 to −0.1)	−1.1 (−4.2 to −0.1)	0.784
PT (degree)	−1.0 (−5.0 to 6.0)	−1.0 (−2.0 to 6.0)	−2.0 (−6.0 to 6.0)	0.215	6.0 (−1.0 to 6.0)	−2.0 (−6.0 to 6.0)	0.314	−2.0 (−6.0 to 6.0)	1.0 (−2.0 to 6.0)	0.467
PI-LL (degree)	−4.00 ± 7.02	−2.35 ± 8.00	−6.52 ± 5.71	0.069	8.00 ± 5.57	−5.74 ± 6.07	**<0.001***	−5.78 ± 6.59	−1.91 ± 7.69	0.127
Clinical outcome (Difference between preoperative and postoperative 6 or 12 months data)										
Back VAS	−3.0 (−5.0 to −3.0)	−3.0 (−5.0 to −3.0)	−3.0 (−5.0 to −3.0)	0.694	−2.0 (−3.0 to 1.0)	−4.0 (−5.0 to −3.0)	**0.045***	−5.0 (−5.0 to −3.0)	−3.0 (−5.0 to −3.0)	0.476
Leg VAS	−5.0 (−6.0 to −4.0)	−4.0 (−6.0 to −4.0)	−5.0 (−6.0 to −5.0)	**0.05***	−3.0 (−4.0 to −2.0)	−5.0 (−6.0 to −4.0)	**0.009***	−5.0 (−6.0 to −4.0)	−5.0 (−6.0 to −4.0)	0.697
ODI	−12.76 ± 5.06	−12.00 ± 5.24	−13.38 ± 4.95	0.411	−7.33 ± 5.03	−13.23 ± 4.86	0.052	−13.41 ± 4.92	−11.18 ± 5.29	0.224
SF-36 physical	12.88 ± 5.22	12.44 ± 5.19	13.24 ± 5.35	0.647	7.28 ± 5.93	13.36 ± 4.96	0.051	13.64 ± 5.16	11.01 ± 5.11	0.162
SF-36 mental	14.50 ± 6.10	13.89 ± 6.01	14.99 ± 6.27	0.59	6.77 ± 6.86	15.16 ± 5.66	**0.02***	15.09 ± 5.63	13.05 ± 7.21	0.356
EQ-5D	5.81 ± 1.68	5.50 ± 1.55	6.05 ± 1.77	0.333	4.00 ± 0.00	5.91 ± 1.67	**<0.001***	6.04 ± 1.76	5.20 ± 1.32	0.182

*P-value < 0.05 indicates a significant difference between two groups.

Table 2. Summary of Radiological and Clinical Outcomes

Variable	Preoperative (n = 29 patients/38 Levels)	Postoperative 12 months (n = 29 patients/38 Levels)	Difference	*P*-Value
	Mean ± SD or Median (Q1-Q3)			
Radiological Outcome				
Anterior DH (mm)	9.08 ± 3.38	13.04 ± 1.84	3.97 ± 2.66	**<0.001***
Posterior DH (mm)	5.38 ± 2.00	9.60 ± 1.24	4.22 ± 1.45	**<0.001***
SL (degree)	10.05 ± 5.35	13.06 ± 5.02	3.01 ± 3.19	**<0.001***
LL (degree)	41.0 (26.0–48.0)	44.0 (32.0–53.0)	5.0 (1.0–8.0)	**0.006***
Disc wedge angle (degree)	1.9 (0.4–3.7)	0.6 (0.3–1.2)	−1.0 (−2.7 to −0.1)	**<0.001***
PT (degree)	19.0 (16.0–24.0)	21.0 (16.0–25.0)	−1.0 (−4.0–6.0)	0.619
PI-LL (degree)	17.28 ± 14.39	13.28 ± 12.31	−4.00 ± 7.02	**0.005***
Clinical outcome				
Back VAS	7.0 (6.0–8.0)	3.0 (2.0–4.0)	−3.0 (−5.0 to −3.0)	**<0.001***
Leg VAS	8.0 (7.0–8.0)	3.0 (2.0–4.0)	−5.0 (−6.0 to −4.0)	**<0.001***
ODI	26.89 ± 6.12	14.13 ± 6.36	−12.76 ± 5.06	**<0.001***
SF-36 physical	19.45 ± 4.45	32.33 ± 6.56	12.88 ± 5.22	**<0.001***
SF-36 mental	28.03 ± 4.41	42.53 ± 7.65	14.50 ± 6.10	**<0.001***
EQ-5D	13.65 ± 2.92	19.46 ± 2.92	5.81 ± 1.68	**<0.001***

**P*-value < 0.05 indicates a significant difference between two groups.

Subgroup Analysis Based on Preoperative Malalignment

Preoperative radiographs revealed abnormal LL in 17 patients, abnormal PT in 14 patients, and PI-LL mismatch in 20 patients. In the group with abnormal LL, LL was corrected from a mean of 26° to 36°, with statistically significant improvements in all radiological parameters except PT. In the group with abnormal PT, PT itself did not change significantly, but other radiological outcomes improved significantly. For patients with PI-LL mismatch, mismatch was corrected from 23.75° to 18.45°, with significant improvements in all radiological outcomes except PT. Clinical outcomes improved significantly in all subgroups with preoperative malalignment (Table 3).

Subgroup Analysis of Clinical Outcomes Based on Postoperative Alignment

When comparing clinical outcomes based on postoperative sagittal alignment, no statistically significant differences were observed between the groups with normal and abnormal LL. However, patients with normal PT showed significantly better outcomes in back VAS and ODI ($P = 0.045$ and 0.032, respectively). Patients with normal PI-LL mismatch demonstrated significantly greater improvements in ODI and SF-36 physical scores (both $P = 0.008$) (Table 4).

Subgroup Analysis of Radiological Outcomes Based on Cage Related Data

Analysis of radiographic changes according to cage characteristics showed that larger cage sizes were significantly associated with greater increases in the posterior DH ($P = 0.041$), other alignment related parameters also showed a general trend toward greater correction. Moreover, sagittal alignment correction tended to be more pronounced depending on the cage type. In particular, convex-type cages demonstrated significantly greater restoration of the posterior DH compared to hyper-lordotic cages ($P = 0.005$) (Table 5).

DISCUSSION

The BE-TLIF technique preserves the advantages of conventional biportal endoscopic spine surgery while demonstrating favorable fusion rates and complication profiles. Prior comparative studies have consistently reported that although BE-TLIF may require longer operative time during the early learning curve compared with MIS-TLIF, postoperative outcomes are not significantly different between the 2 techniques, whereas intraoperative blood loss and postoperative drainage tend to be lower with BE-TLIF.[12,13] In the present study, the mean EBL was 177 mL and drainage volume was 123 cc were minimal, clinical outcomes improved significantly from baseline, and all patients were able to ambulate on postoperative day 1 or 2. The relatively longer hospital stay reflects characteristics of our national insurance system, in which prolonged hospitalization imposes minimal financial burden. Consequently, our institution routinely performs postoperative MRI and laboratory evaluation on day 7 before discharge, accounting for the mean HOD of 8.97 days.

Table 3. Subgroup Analysis Based on Preoperative Malalignment in Radiological Data

	LL malalignment (n = 17 patients)				PT malalignment (n = 14 patients)				PI-LL Mismatch (n = 20 patients)			
	Preop (n = 17)	Postop 12 months (n = 13)	Difference		Preop (n = 14)	Postop 12 months (n = 16)	Difference		Preop (n = 20)	Postop 12 months (n = 12)	Difference	
Variable	**Mean ± SD or Median (Q1-Q3)**			***P*-Value**	**Mean ± SD or Median (Q1-Q3)**			***P*-Value**	**Mean ± SD or Median (Q1-Q3)**			***P*-Value**
Radiological outcome												
Anterior DH	9.14 ± 3.44	13.14 ± 2.05	4.00 ± 2.59	**<0.001***	9.44 ± 3.87	13.41 ± 1.78	3.97 ± 2.76	**<0.001***	8.98 ± 2.91	13.07 ± 1.98	4.09 ± 2.29	**<0.001***
Posterior DH	5.35 ± 2.05	9.70 ± 1.25	4.36 ± 1.42	**<0.001***	5.41 ± 2.14	9.47 ± 1.36	4.06 ± 1.48	**<0.001***	5.25 ± 1.96	9.57 ± 1.37	4.32 ± 1.39	**<0.001***
SL	8.98 ± 5.40	12.27 ± 5.39	3.29 ± 3.31	**<0.001***	10.56 ± 5.22	13.71 ± 4.62	3.14 ± 3.63	**0.001***	9.66 ± 5.63	12.56 ± 5.23	2.91 ± 3.04	**<0.001***
LL	26.0 (24.0—38.0)	36.0 (31.0—45.0)	6.0 (3.0—10.0)	**0.041***	38.5 (24.0—44.0)	42.5 (32.0—52.0)	7.0 (4.0—9.0)	**0.047***	30.0 (24.5—44.0)	37.0 (31.0—48.5)	6.0 (3.5—9.5)	**0.005***
Disc wedge angle	1.6 (0.4—4.2)	0.5 (0.3—1.2)	−0.8 (−3.1 to 0.1)	**<0.001***	1.6 (0.4—3.3)	0.6 (0.2—1.2)	−0.3 (−2.3 to 0.0)	**0.002***	2.0 (0.4—4.2)	0.5 (0.2—1.2)	−1.1 (−3.1 to 0.1)	**<0.001***
PT	20.0 (17.0—26.0)	22.0 (16.0—25.0)	−2.0 (−4.0 to 6.0)	>0.999	25.0 (23.0—32.0)	23.0 (20.0—30.0)	−1.5 (−5.0 to 6.0)	0.679	22.5 (19.0—28.0)	22.0 (17.5—25.0)	−1.5 (−4.5 to 5.0)	0.681
PI-LL	19.06 ± 14.93	14.41 ± 11.51	−4.65 ± 7.66	**0.024***	23.36 ± 11.46	18.00 ± 9.11	−5.36 ± 7.95	**0.026***	23.75 ± 12.51	18.45 ± 10.74	−5.30 ± 7.06	**0.003***
Clinical outcome												
Back VAS	7.0 (6.0—8.0)	3.0 (2.0—3.0)	−3.0 (−5.0 to 3.0)	**<0.001***	7.0 (6.0—8.0)	3.0 (2.0—4.0)	−3.0 (−5.0 to 3.0)	**<0.001***	7.0 (6.0—8.0)	3.0 (2.0—4.0)	−5.0 (−5.0 to 3.0)	**<0.001***
Leg VAS	8.0 (7.0—8.0)	2.0 (1.0—4.0)	−6.0 (−6.0 to 4.0)	**<0.001***	8.0 (7.0—8.0)	2.0 (2.0—4.0)	−5.0 (−6.0 to 4.0)	**<0.001***	8.0 (7.0—8.0)	2.0 (1.0—3.0)	−6.0 (−6.0 to 4.0)	**<0.001***
ODI	26.60 ± 6.58	13.80 ± 6.47	−12.80 ± 4.71	**<0.001***	26.47 ± 6.96	14.05 ± 6.18	−12.42 ± 4.80	**<0.001***	26.93 ± 6.83	13.67 ± 7.07	−13.26 ± 5.39	**<0.001***
SF-36 physical	19.06 ± 4.80	32.31 ± 6.84	13.24 ± 5.19	**<0.001***	19.06 ± 5.12	32.03 ± 7.03	12.97 ± 5.79	**<0.001***	18.94 ± 4.11	31.61 ± 7.05	12.67 ± 5.73	**<0.001***
SF-36 mental	28.66 ± 4.58	43.85 ± 8.50	15.19 ± 6.22	**<0.001***	27.25 ± 4.11	42.17 ± 8.17	14.92 ± 6.81	**<0.001***	28.69 ± 4.46	43.42 ± 8.73	14.73 ± 6.62	**<0.001***
EQ-5D	13.84 ± 3.06	19.56 ± 3.12	5.72 ± 1.86	**<0.001***	14.50 ± 2.77	19.89 ± 2.83	5.39 ± 1.61	**<0.001***	14.27 ± 3.01	20.08 ± 2.97	5.81 ± 1.63	**<0.001***

*P-value < 0.05 indicates a significant difference between two groups.

Table 4. Subgroup Analysis of Clinical Outcome With Postoperative Sagittal Alignment Parameters

	Postoperative LL			Postoperative PT			Postoperative PI-LL		
	Normal	Malalignment		Normal	Malalignment		Normal	Mismatch	
Variable	Mean ± SD or Median (Q1-Q3)		*P*-Value	Mean ± SD or Median (Q1-Q3)		*P*-Value	Mean ± SD or Median (Q1-Q3)		*P*-Value
Back VAS	3.0 (2.0—4.0)	3.0 (2.0—4.0)	0.408	2.0 (2.0—3.0)	3.0 (3.0—4.0)	**0.045***	3.0 (2.0—4.0)	3.0 (2.0—4.0)	0.273
Leg VAS	3.0 (3.0—4.0)	2.0 (1.0—3.0)	0.27	2.0 (1.0—3.0)	3.0 (2.0—4.0)	0.097	3.0 (1.0—3.0)	3.0 (2.0—4.0)	0.182
ODI	14.50 ± 4.64	13.80 ± 7.70	0.734	11.87 ± 5.78	15.61 ± 6.41	**0.032***	12.47 ± 5.80	15.22 ± 6.60	**0.008***
SF-36 physical	33.36 ± 5.77	31.40 ± 7.23	0.366	33.90 ± 6.01	31.30 ± 6.83	0.239	35.75 ± 6.38	30.09 ± 5.78	**0.008***
SF-36 mental	40.56 ± 5.48	44.31 ± 8.94	0.125	43.91 ± 4.86	41.63 ± 9.01	0.32	43.86 ± 6.06	41.66 ± 8.54	0.392
EQ-5D	18.61 ± 2.62	20.26 ± 3.03	0.086	20.33 ± 2.64	18.86 ± 3.01	0.135	19.33 ± 3.06	19.55 ± 2.89	0.832

*P-value < 0.05 indicates a significant difference between two groups.

Although previous comparative studies have shown no major radiologic or clinical differences between BE-TLIF and other fusion techniques, concerns remain regarding limited bone graft volume, continuous saline irrigation, and a narrow working space—factors theoretically associated with lower fusion rates or increased subsidence. In degenerative lumbar disease, disc space narrowing and bony hypertrophy may further constrain cage size in BE-TLIF. To overcome these challenges, recent studies have focused on optimizing cage materials, footprint, and expandable designs. Kim et al. demonstrated that using an OLIF-type cage in BE-TLIF achieved a 94.2% fusion rate at postoperative 18 months with significant restoration of SL and DH, likely due to improved load distribution and engagement of bilateral epiphyseal rings.[2,14] Pao JL et al. reported 100% fusion without subsidence at one year using PEEK and titanium coated PEEK cages.[3] Park et al. described strategies such as a skin incision at pedicle lateral margin, making additional medial portal, and use of 3D printed porous titanium cages to enhance fusion.[15] Another study have found no difference in fusion or subsidence between PEEK and titanium cages but suggested that wider cages (>11 mm) improve endplate stability by increasing contact area.[4] Park et al. reported that the use of a dual-expandable cage in BE-TLIF resulted in significant increases in DH, SL, and LL with no cases of subsidence observed.[16] Additionally, a systematic review and meta-analysis comparing expandable and static cages in TLIF demonstrated that expandable cages achieved greater restoration of anterior DH (+2.14 mm), posterior DH (+0.64 mm), foraminal height (+1.60 mm), and SL (+1.56°) than static cages. However, there were no significant differences in LL, clinical outcomes (VAS, ODI), fusion rates, or cage subsidence between the 2 designs.[17]

Also in recently, vertebral endplate cortical fracture (VECF) has recently been recognized as an important radiographic marker of early biomechanical instability following lumbar interbody

Table 5. Subgroup Analysis of Radiological Outcomes According to Cage Characteristics

	Cage Size			Cage Type		
	28 mm	32 mm		Convex	Hyper-lordotic	
Variable	Mean ± SD or Median (Q1-Q3)		*P*-Value	Mean ± SD or Median (Q1-Q3)		*P*-Value
Δ Anterior DH (mm)	3.45 ± 3.13	4.48 ± 2.05	0.237	3.34 ± 3.30	4.38 ± 2.13	0.245
Δ Posterior DH (mm)	3.74 ± 1.32	4.69 ± 1.45	**0.041***	4.73 ± 1.19	3.43 ± 1.49	**0.005***
Δ SL (degree)	2.71 ± 3.93	3.30 ± 2.29	0.577	2.57 ± 3.18	3.29 ± 3.23	0.501
Δ LL (degree)	4.0 (1.0—7.0)	7.0 (4.0—11.0)	0.076	4.0 (1.0—10.0)	6.0 (4.0—9.0)	0.454
Δ Disc wedge angle (degree)	−1.1 (−2.0 to 0.0)	−0.8 (−3.9 to −0.2)	0.255	−1.1 (−3.8 to −0.2)	−0.6 (−2.0 to 0.0)	0.262
Δ PT (degree)	−1.0 (−2.0 to 6.0)	−2.0 (−6.0 to 8.0)	0.93	−2.0 (−6.0 to 6.0)	2.0 (−2.0 to 6.0)	0.224
Δ PI-LL (degree)	−2.63 ± 7.22	−6.68 ± 6.43	0.076	−3.40 ± 8.18	−5.48 ± 6.26	0.382

*P-value < 0.05 indicates a significant difference between two groups.

fusion. VECF is attributed to micromotion at the cage—endplate interface, inadequate load transfer, and delayed early osteointegration. Sasaki et al. reported significant differences in VECF incidence by cage material—65% for PEEK, 44% for titanium, 69% for titanium coated PEEK, and 23% for porous tantalum—in 84 cases of single-level PLIF or TLIF.[18] In a prospective study, Segi et al. found increased VECF with Titanium coated PEEK cages due to load imbalance between the peripheral cage surface and central window, whereas porous tantalum cages—with cancellous bone-like modulus and interconnected porosity—demonstrated reduced micromotion and significantly lower VECF rates.[19] Although detailed CT-based analysis of VECF was not performed in our study due to its single-arm design, these findings offer an important framework for interpreting endplate behavior in BE-TLIF.

The present study primarily sought to evaluate whether the combination of rh-BMP2 and a bullet-type expandable cage could achieve acceptable fusion and subsidence outcomes within the BE-TLIF environment. Recent evidence suggests that rh-BMP2 markedly accelerates fusion, particularly in osteoporotic patients. Kim et al. reported that rh-BMP2 patients achieved fusion at approximately 2.5 years compared with more than 4 years in the non-BMP group, with the disparity increasing to 3 versus 5 years in osteoporotic patients.[20] Park et al. similarly demonstrated that rh-BMP2 produced fusion rates comparable to or higher than local autograft in PLIF, mitigating early mechanical instability through strong osteoinductive activity.[21] Thus, rh-BMP2 may reduce micromotion and early endplate stress, enhancing biological stability during the critical early fusion period.

Expandable cages, likewise, provide several mechanical advantages, including facilitated insertion through a narrow corridor, decreased impaction force, and gradual expansion that minimizes focal endplate stress.[22-24] In the present study, despite the average cage footprint being relatively small (334 mm^2; approximately half that of ALIF cages), the fusion rate at 12 months was 92.11%. Subsidence occurred in 11 of 38 levels (28.95%), with clinically significant subsidence ($\geq$2 mm) in 4 levels (10.53%); 2 cases were attributable to early endplate injury during the learning curve. These findings are comparable to subsidence rates reported in MIS-TLIF and PLIF using static cages and support the non-inferiority of single expandable cage constructs when combined with rh-BMP2.

Proper cage alignment was facilitated by a right-sided approach aligned with natural lumbar lordosis, minimizing endplate damage. In this context, cage-related parameters—material, size, and insertion position—did not significantly influence fusion or subsidence, suggesting that meticulous endplate preparation, preservation of posterior stabilizing structures, and rh-BMP2-enhanced biological environment play a more decisive role in promoting successful fusion than cage footprint alone.

Sagittal alignment has also emerged as an important consideration even in short-segment fusion. Residual PI—LL mismatch has been associated with persistent pain, functional limitations, and increased reoperation rates.[25-27] Although expandable cages have theoretical advantages in restoring DH and SL even with a smaller footprint, prior meta-analyses have shown no significant superiority of expandable over static cages in sagittal correction. In the present study, DH, PH, SL, and LL all improved postoperatively; however, these findings should not be interpreted as evidence that a single expandable cage provides enhanced sagittal correction. Rather, the degree of correction observed was within the range reported in static cage studies and in some cases was less than expected. Potential explanations include premature anterior locking of the cage when encountering the endplate, limited footprint reducing effective expansion force, and symmetric expansion mechanics.

The PI—LL mismatch improved from 17.28° to 13.28°, and subgroup analysis of patients with abnormal preoperative sagittal parameters demonstrated significant improvement in LL, PT, and PI—LL mismatch, although PT correction remained limited. Residual PT was associated with persistent back pain, whereas residual PI—LL mismatch correlated with functional impairment. These findings reinforce the importance of achieving sagittal alignment within normal range, even in short-segment fusion.

In addition to the few limitations discussed above, this study has several other limitations. First, the retrospective nature and single-institution design introduce potential selection bias; multicenter prospective studies are required to validate our findings. Second, the lack of a control group using static or other expandable cages limits direct comparison. Finally, the average follow-up period of one year is relatively short; longer-term radiologic and clinical data beyond two years will be necessary to determine durability of outcomes.

CONCLUSIONS

BE-TLIF using a single bullet-type expandable cage combined with rh-BMP2 demonstrated radiologic and clinical outcomes, including meaningful sagittal alignment correction, that were comparable to those reported for MIS-TLIF and PLIF with static cages. These findings support the non-inferiority of this construct and highlight the synergistic biomechanical and biological stability provided by expandable cage mechanics and rh-BMP2.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Sub-Ri Park: Conceptualization, Formal analysis, Writing — original draft, Writing — review & editing. **Namhoo Kim:** Conceptualization, Formal analysis, Writing — original draft. **Ji-Won Kwon:** Data curation, Methodology, Software. **Kyung-Soo Suk:** Supervision. **Hak-Sun Kim:** Supervision. **Seong-Hwan Moon:** Methodology, Software. **Si-Young Park:** Data curation, Methodology, Software. **Byung Ho Lee:** Data curation, Methodology, Software. **Jae-Won Shin:** Data curation, Methodology, Software. **Jin-Oh Park:** Conceptualization, Supervision.

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Availability of Data and Materials: The data that support the findings of this study are available from the corresponding author, Jin-Oh Park, upon reasonable request.

Ethics Approval and Consent to Participate: Approval was obtained from the Institutional Review Board (approval number: 9-2025-0077). The requirement for informed consent was waived owing to the retrospective nature of the study.

Conflict of Interest: The authors declare that the article content was composed in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received 21 November 2025; accepted 27 November 2025

Citation: World Neurosurg. (2026) 205:124698.
http://doi.org/10.1016/j.wneu.2025.124698

Journal homepage: ***www.journals.elsevier.com/world-neurosurgery***

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