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What Affects Segmental Lordosis of the Surgical Site after Minimally Invasive Transforaminal Lumbar Interbody Fusion?

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Purpose: This study was undertaken to identify factors that affect segmental lordosis (SL) after minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) by comparing patients whose postoperative SL increased with those whose decreased.
Materials and Methods: Fifty-five patients underwent MIS-TLIF at our institute from January 2018 to September 2019. Demographic, pre- and postoperative radiologic, and cage-related factors were included. Statistical analyses were designed to compare patients whose SL increased with decreased after surgery.
Results: After surgery, SL increased in 34 patients (group I) and decreased in 21 patients (group D). The index level, disc lordosis, SL, lumbar lordosis, proximal lordosis (PL), and Y-axis position of the cage (Yc) differed significantly between groups I and D. The cage in group I was more anterior than that in group D (Yc: 55.84% vs. 51.24%). Multivariate analysis showed that SL decreased more significantly after MIS-TLIF when the index level was L3/4 rather than L4/5 [odds ratio (OR): 0.46, p=0.019], as preoperative SL (OR: 0.82, p=0.037) or PL (OR: 0.68, p=0.028) increased, and as the cage became more posterior (OR: 1.10, p=0.032).
Conclusion: Changes in SL after MIS-TLIF appear to be associated with preoperative SL and PL, index level, and Yc. An index level at L4/5 instead of L3/4, smaller preoperative SL or PL, and an anterior position of the cage are likely to result in increased SL after MIS-TLIF.

Key Words: Minimally invasive, transforaminal lumbar interbody fusion, lumbar lordosis, cage, outcome, spine surgery, segmental lordosis

INTRODUCTION

Interbody fusion is widely used to treat degenerative diseases of the spine. Many techniques have been developed to decompress and restore sagittal alignment, including anterior lumbar interbody fusion (ALIF), lateral lumbar interbody fusion (LLIF), transforaminal lumbar interbody fusion (TLIF), and posterior lumbar interbody fusion. Many authors have emphasized the importance of adequately restoring sagittal alignment by means of interbody fusion[1,2] because it is associated with both adjacent segment disease after surgery and clinical outcomes.

Recently, minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) using a single cage and percutaneous pedicle screw fixation has become popular. MIS-TLIF has many advantages over conventional TLIF:[3-11] It utilizes smaller surgical incisions, poses less damage to paraspinal muscles, and causes less bleeding during surgery. Furthermore, it is associated with shorter hospitalization and a shorter postoperative period with an external brace.

Unlike in conventional surgery, the cage plays a major role

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in creating lordosis in MIS surgery, because it requires less dissection of paraspinal tissue and a more limited extent of osteotomy. Many studies have reported a relationship between cage characteristics and lordosis.[12-22] However, how cage position affects postoperative lordosis after MIS-TLIF has only been studied indirectly by comparing dichotomized groups of anterior or posterior cage positioning.[14,19] In this study, we sought to identify factors that may affect segmental lordosis (SL) after MIS-TLIF by comparing patients whose SL increased with those whose decrease.

MATERIALS AND METHODS

We performed a retrospective analysis in patients who underwent MIS-TLIF for degenerative lumbar disease at our institute from January 2018 to September 2019. We set our exclusion criteria to control variables and achieve coherent data. Our exclusion criteria included the following: revision cases (adjacent level had undergone laminectomy or fusion previously), index level for surgery of L1/2, 2/3, or L5/S1, more than one interbody fusion level, and missing data. In that way, we included patients who received MIS-TLIF at only one index level (L3/4 or L4/5) with a CAPSTONE® PEEK cage (Medtronic, Minneapolis, MN, USA) and ARTeMIS® percutaneous screws (Medyssey, Buffalo, IL, USA) for lumbar degenerative disease (Fig. 1). The Human Research Protection Center of our university waived the need for Institutional Review Board approval, and the Institutional Review Board of Gangnam Severance Hospital, Yonsei University College of Medicine approved this study (No. 3-2020-0150).

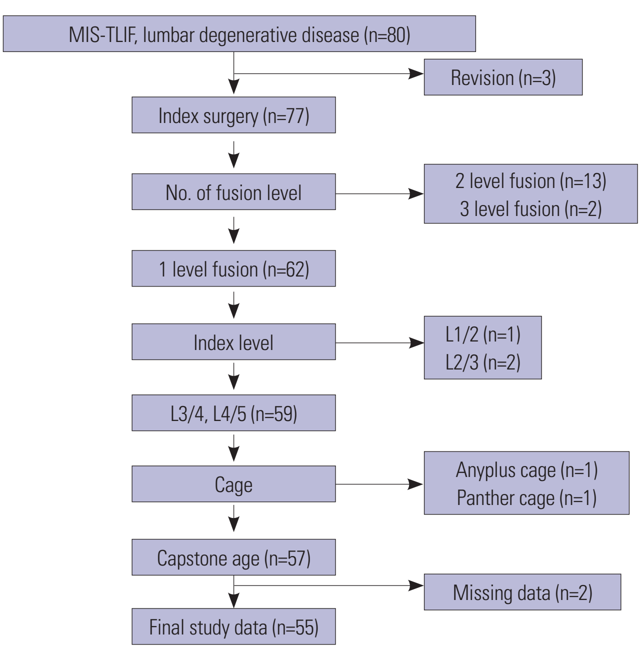

Fig. 1. Flow diagram for patient selection. MIS-TLIF, minimally invasive transforaminal lumbar interbody fusion.

Parameters

We examined 33 parameters, which we divided into demographic, pre- and postoperative radiologic, and cage-related parameters. The demographic parameters were age, sex, diagnosis, and index level of surgery. The pre- and postoperative radiologic parameters were disc lordosis (DCL), anterior disc height (DHA), posterior disc height (DHP), SL, lumbar lordosis (LL), proximal lordosis (PL), distal lordosis (DL), pelvic incidence (PI), pelvic tilt (PT), sacral slope (SS), and PI-LL, which were measured on postoperative 1-year standing lumbar x-ray images. The detailed measurement method for the radiologic parameters is shown in Fig. 2. DCL was defined as the angle

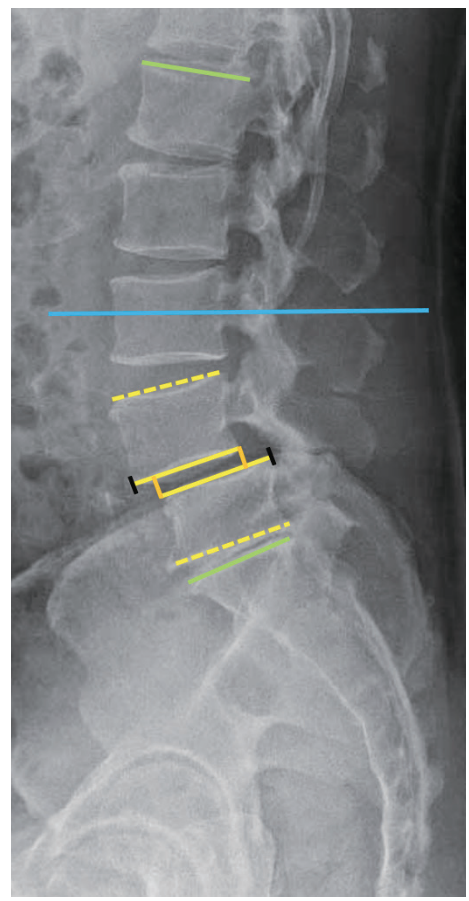

Fig. 2. Preoperative radiologic parameters. Disc lordosis (DCL): angle between the inferior endplate of the upper vertebra and the superior endplate of the lower vertebra of the index level (yellow line), Segmental lordosis (SL): angle between the superior endplate of the upper vertebra and the inferior endplate of the lower vertebra of the index level (yellow dotted line). Anterior disc height (DHA): perpendicular distance between the superior endplate of the anterior end of the lower vertebra and the inferior endplate of the upper vertebra of the index level (anterior orange line). Posterior disc height (DHP): perpendicular distance between the inferior endplate at the posterior end of the upper vertebra and the superior endplate of the lower vertebra of the index level (posterior orange line). Lumbar lordosis (LL): angle between the superior endplate of L1 and the superior endplate of S1 (green line). Proximal lordosis (PL): angle between a horizontal line (blue line) and the superior endplate of the L1 vertebra (superior green line). Distal lordosis (DL): angle between a horizontal line and the superior endplate of S1 (inferior green and blue line).

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between the inferior endplate of the upper vertebra of the index level and the superior endplate of the lower vertebra of the index level. SL was defined as the angle between the superior endplate of the upper vertebra of the index level and the inferior endplate of the lower vertebra of the index level. DHA was defined as the perpendicular distance between the anterior end of the superior endplate of the lower vertebra of the index level and the inferior endplate of the upper vertebra of the index level. DHP was defined as the perpendicular distance between the posterior end of the inferior endplate of the upper vertebra of the index level and the superior endplate of the lower vertebra of the index level. LL was defined as the angle between the superior endplate of the L1 vertebra and the superior endplate of the S1 vertebra. PL was defined as the angle between a horizontal line and the superior endplate of the L1 vertebra. DL was defined as the angle between a horizontal line and the superior endplate of the S1 vertebra. We used previously published definitions for PI, PT, and SS.[23]

The cage-related parameters were cage height, cage length, insertion side of the cage, X-axis position of the cage (Xc), Y-axis position of the cage (Yc), and transverse angle of the cage (angle), all of which were measured on postoperative 1-year supine computed tomography (CT) images (Fig. 3). The center of the cage was defined as the intersection of the two diagonals of the cage on an axial CT image. The corner of the vertebral body was determined by approximating an ellipse, and the X and Y axes were then determined accordingly. The position of the cage was converted to a ratio by comparing the X and Y diameters of the ellipse. If Xc was less than 50%, the cage was located on the right, and if it was more than 50%, the cage was located on the left. If Yc was less than 50%, the cage was located at the posterior, and if it was more than 50%, the cage was located at the anterior. The angle of the cage was determined using the long axis of the cage and the X axis of the ellipse, such that the cage position became more transverse as the angle became smaller. The preoperative radiologic parameters were acquired from a preoperative whole standing x-ray obtained at the outpatient clinic before surgery. The cage-related parameters were obtained from medical records and axial images of the postoperative 1-year lumbar CT. Postoperative radiologic parameters were obtained from postoperative 1-year standing X-ray. Radiographic evaluation of fusion integrity was evaluated with postoperative 1-year CT based on the Bridwell interbody fusion grading system as follows: 1) fused with remodeling and trabeculae present; 2) graft intact, not fully remodeled and incorporated, with no lucency; 3) graft intact, potential lucency present at the top and bottom of the graft; and 4) fusion absent with collapse and/or resorption of graft. If a patient's Bridwell grade was I or II, we considered fusion to have been achieved, otherwise we considered fusion as incomplete. All of the above parameters were measured by two spine surgeons (S.H.K and B.S.H) and averaged. There was no parameter with disagreement in terms of direction of the parameter change (e.g., one measured parameter increased after surgery, and the other measure parameter decreased after surgery).

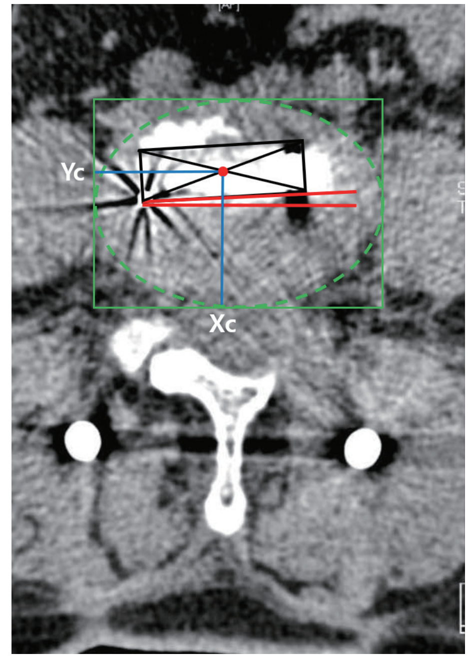

Fig. 3. Cage location–related radiologic variables. The center of the cage (red circle) was determined using the diagonal intersection of the cage on an axial CT image. The corner of the vertebral body was determined by approximating an ellipse, and the X and Y axes were determined accordingly (green solid line). The cage position (blue line) was converted into a ratio by comparing the X and Y diameters of the ellipse. If Xc was less than 50%, the cage was located on the right, and if it was more than 50%, the cage was located on the left. If Yc was less than 50%, the cage was located at the posterior, and if it was more than 50%, the cage was located at the anterior. The angle of the cage was determined using the long axis of the cage and the X axis of the ellipse (red angle). Therefore, the smaller the angle, the more transversely the cage is positioned. Yc, Y-axis position of the cage; Xc, X-axis position of the cage.

Operative technique

Surgery was performed by a single surgeon at a single institute who has written numerous articles about MIS-TLIF and has obtained more than 15 years of experience with performing MIS-TLIF operations.[5,6,24-28] The surgical techniques for MIS-TLIF were the same as those described in our previous study.[5,6,25] We also performed contralateral decompression, although contralateral facets were not removed. We used a specific process to place cages more anterior for more effective creation of lordosis. After the cage was inserted through the facetectomy side, a cage pusher was place on the end closest to the surgeon toward the lateral side and struck with a mallet so that it could be rotated and positioned more horizontally, compared to its initial location. Finally, to place the cage as anterior as possible, the cage impactor was place on the center of the cage and struck with a mallet until resistance from the anterior annulus was sensed. The CAPSTONE® PEEK cage we used was non expandable, non-lordotic, and bullet-shaped with a 10-mm width.

The cage length was either 32 or 36 mm, which was selected on the basis of the patient's preoperative images and intraoperative measurement.

Statistical analysis

All continuous variables were tested for normality using the Shapiro-Wilk test and Kolmogorov Smirnov test. Continuous variables are expressed as means±standard deviations or medians (interquartile ranges, 25% to 75%). Categorical variables are expressed as frequencies and percentages. Continuous variables were analyzed with either independent two-sample t-testing or the Mann-Whitney U test, depending on the data nor-

Table 1. Patient Demographic Data, Radiologic and Cage-Related Paremeters

	Total (n=55)	Increase (n=34)	Decrease (n=21)	*p* value*
Demographics				
Sex				0.761
Male	25 (45.5)	16 (47.1)	9 (42.9)	
Female	30 (54.5)	18 (52.9)	12 (57.1)	
Age (yr)	59.47±11.83	59.85±10.89	59.86±13.47	0.765
Diagnosis				0.947
Stenosis	17 (30.9)	10 (29.4)	7 (33.3)	
Deg listhesis	29 (52.7)	18 (53.0)	11 (52.4)	
Lytic listhesis	5 (9.1)	3 (8.8)	2 (9.5)	
Massive HLD	4 (7.3)	3 (8.8)	1 (4.8)	
Indication level				0.020
L3/4	8 (14.5)	2 (5.9)	6 (28.6)	
L4/5	47 (85.5)	32 (94.1)	15 (71.4)	
Preoperative radiologic parameters				
Disc				
Disc lordosis (°)	6.34±4.78	5.15±5.02	8.27±3.70	0.017
Anterior height (mm)	9.96±3.81	9.44±3.76	10.81±3.83	0.198
Posterior height (mm)	7.09±2.55	7.26±2.77	6.80±2.18	0.521
Segmental lordosis (°)	13.90±6.14	12.40±6.18	16.31±5.39	0.020
Lumbar lordosis (°)	43.58±9.73	41.29±9.38	47.28±9.34	0.025
Proximal lordosis (°)	11.87±7.45	9.40±6.37	15.86±7.47	0.001
Distal lordosis (°)	31.71±5.41	31.90±5.62	31.41±5.18	0.751
Pelvic parameters (°)				
Pelvic incidence	50.73±10.56	51.03±11.80	50.25±8.44	0.795
Pelvic tilt	18.22±8.49	18.81±9.21	17.27±7.29	0.519
Sacral slope	32.49±6.20	32.22±6.21	32.93±6.31	0.686
Pelvic incidence-lumbar lordosis	13.28±8.25	10.49±14.45	5.66±10.64	
Cage-related parameters				
Height (mm)	11.36±1.10	11.18±1.11	11.67±1.02	0.107
Length (mm)				0.348
32	27 (49.1)	15 (44.1)	12 (57.1)	
36	28 (50.9)	19 (55.9)	9 (42.9)	
Insertion side				0.418
Right	30 (54.5)	20 (58.8)	10 (47.6)	
Left	25 (45.5)	14 (41.2)	11 (52.4)	
X-axis position (%)	50.53±6.10	50.79±6.25	50.12±5.99	0.698
Y-axis position (%)	54.08±7.50	55.84±7.39	51.24±6.92	0.026
Transverse angle (°)	16.54±14.26	15.41±13.53	18.37±15.54	0.460
Fusion status				0.250
Fusion	44 (80.0)	28 (75.7)	16 (88.9)	
No fusion	11 (20.0)	9 (24.3)	2 (11.1)	

HLD, herniated lumbar disc.
Data are presented as mean±standard deviation or n (%).
*Statistical analyses were performed to compare patients whose postoperative segmental lordosis increased with those whose decreased.

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mality. The chi-square test and Fisher's exact test were used to identify significant differences between categorical variables. *P*<0.05 was considered statistically significant. Variables with a *p*<0.05 were collected from the univariable logistic regression. To consider multicollinearity, variables with a variance inflation factor higher than 5 were excluded. The remaining variables were entered into final multivariable logistic regression. Statistical analyses were performed using SAS (version 9.4, SAS Inc., Cary, NC, USA).

RESULTS

Patient demographics

Overall, 80 patients received MIS-TLIF for lumbar degenerative disease at our institute from January 2018 to September 2019. Based on our selection criteria, 55 patients were included in the analysis. The patient demographics are shown in Table 1.

Comparison of preoperative and postoperative radiologic parameters

DCL (6.34±4.78° vs. 8.96±4.11°, *p*<0.001), DHA (9.96±3.81 mm vs. 12.96±2.31 mm, *p*<0.001), and DHP (7.09±2.55 mm vs. 8.16±1.78 mm, *p*=0.001) were significantly higher after surgery. SL was higher after surgery, but the difference was not statistically significant (13.90±6.14° vs. 15.09±5.98°, *p*=0.072). LL (43.58±9.73° vs. 38.77±10.47°, *p*=0.001) and PL (11.87±7.45° vs. 8.77±6.14°, *p*=0.001) were significantly smaller after surgery. DL was smaller after surgery, but the difference was not statistically significant (31.71±5.41° vs. 29.99±8.99°, *p*=0.134). PI did not change significantly after surgery (50.73±10.56° vs. 51.65±11.06°, *p*=0.231). PT increased significantly after surgery (18.22±8.49° vs. 21.00±7.53°, *p*<0.001). SS decreased significantly after surgery (32.49±6.20° vs. 30.64±6.20°, *p*=0.032). PI-LL increased significantly after surgery (7.15±13.13° vs. 12.88±12.34°, *p*=0.002) (Table 2).

Comparison according to changes in segmental lordosis after surgery

After surgery, SL increased in 34 patients (group I) and decreased in 21 patients (group D) (Table 1). The index level of surgery differed significantly between groups I and D (*p*=0.020). In group I, the index level was L4/5 in 94.1% of patients and L3/4 in 5.9%. In contrast, the index level in group D was L4/5 in 71.4% of patients and L3/4 in 28.6%. Among the preoperative radiologic parameters, DCL, SL, LL, and PL differed significantly between the groups: DCL (5.15±5.02° vs. 8.27±3.70°, *p*=0.017), SL (12.40±6.18° vs. 16.31±5.39°, *p*=0.020), LL (41.29±9.38° vs. 47.28±9.34°, *p*=0.025), and PL (9.40±6.37° vs. 15.86±7.47°, *p*=0.001) were all significantly smaller in group I than in group D. Among the cage-related parameters, Yc differed significantly between the groups. The cages in group I were more anterior than those in group D (55.84±7.39% vs. 51.24±6.92%, *p*=0.026).

Table 2. Comparison of Changes in Segmental Lordosis after Minimally Invasive Transforaminal Lumbar Interbody Fusion

	Preoperative	Postoperative	*p* value
Disc			
Disc lordosis (°)	6.34±4.78	8.96±4.11	<0.001
Anterior height (mm)	9.96±3.81	12.96±2.31	<0.001
Posterior height (mm)	7.09±2.55	8.16±1.78	0.001
Segmental lordosis (°)	13.90±6.14	15.09±5.98	0.072
Lumbar lordosis (°)	43.58±9.73	38.77±10.47	0.001
Proximal lordosis (°)	11.87±7.45	8.77±6.14	0.001
Distal lordosis (°)	31.71±5.41	29.99±8.99	0.134
Pelvic parameters (°)			
Pelvic incidence	50.73±10.56	51.65±11.06	0.231
Pelvic tilt	18.22±8.49	21.00±7.53	<0.001
Sacral slope	32.49±6.20	30.64±6.20	0.032
Pelvic incidence-lumbar lordosis	7.15±13.13	12.88±12.34	0.002

Data are presented as mean±standard deviation.

In regards to fusion rate, there was no difference between groups (75.7 % vs. 88.9%).

Multivariate analysis of changes in segmental lordosis after surgery

According to univariate logistics regression, an increase in postoperative SL was significantly associated with the index level and preoperative DCL, SL, LL, PL, and Yc values (Table 3). Postoperative SL decreased when the index level was L3/4, compared with L4/5 [odds ratio (OR): 0.16; 95% confidence interval 0.03–0.87, *p*=0.034]. Postoperative SL also decreased as preoperative DCL (OR: 0.86; 0.75–0.98, *p*=0.023), preoperative SL (OR: 0.89; 0.80–0.99, *p*=0.027), preoperative LL (OR: 0.93; 0.87–0.99, *p*=0.031), or preoperative PL (OR: 0.87; 0.79–0.96, *p*=0.004) increased. Postoperative SL increased as the cage became more anterior (OR: 1.10; 1.01–1.19, *p*=0.032). Multivariate analysis showed that the index level, preoperative SL, PL, and Yc were significantly associated with an increase in postoperative SL. Postoperative SL decreased significantly, when the index level was L3/4, compared with L4/5 (OR: 0.46; 0.04–0.60, *p*=0.019), when preoperative SL (OR: 0.82; 0.68–0.99, *p*=0.037) or PL (OR: 0.68; 0.50–0.94, *p*=0.028) increased, and when the cage became more posterior (OR: 1.10; 1.01–1.19, *p*=0.032) (Table 3).

DISCUSSION

An increase in lordosis is somewhat anticipated after surgery. However, a significant increase in SL after MIS-TLIF was not recorded in this study. This is in line with the study of Champagne, et al.,[29] who investigated sagittal balance after TLIF, MIS-TLIF, and LLIF. Only LLIF improved SL after surgery. Unlike LLIF, which is executed to restore lordosis and increase the foraminal height of flatback patients, MIS-TLIF is performed to treat various degenerative lumbar diseases, such as spondylo-

Table 3. Logistic Regression between Increased and Decreased Segmental Lordosis after Minimally Invasive Transforaminal Lumbar Interbody Fusion

	Univariate (95% CI)	*p* value	Multivariate (95% CI)	*p* value
Sex				
Male	Reference			
Female	0.844 (0.282–2.524)	0.761		
Age	1.007 (0.962–1.055)	0.760		
Diagnosis				
Stenosis	Reference			
Lytic listhesis	0.476 (0.041–5.577)	0.555		
Deg listhesis	0.545 (0.050–5.919)	0.618		
Massive HLD	0.500 (0.028–8.952)	0.638		
Indication level				
L3/4	0.156 (0.028–0.867)	0.034	0.46 (0.04–0.60)	0.019
L4/5	Reference			
Preoperative radiologic parameters				
Disc				
Disc lordosis	0.855 (0.747–0.979)	0.023	0.98 (0.81–1.18)	0.791
Anterior height	0.906 (0.780–1.053)	0.906		
Posterior height	1.075 (0.865–1.335)	0.514		
Segmental lordosis	0.890 (0.803–0.987)	0.027	0.82 (0.68–0.99)	0.037
Lumbar lordosis (L1-S1)	0.932 (0.874–0.994)	0.031	1.18 (0.97–1.44)	0.095
Proximal lordosis	0.871 (0.792–0.957)	0.004	0.68 (0.50–0.94)	0.028
Distal lordosis	1.017 (0.918–1.126)	0.746		
Pelvic parameters				
Pelvic incidence	1.007 (0.956–1.061)	0.790		
Pelvic tilt	1.022 (0.958–1.091)	0.511		
Sacral slope	0.981 (0.898–1.073)	0.680		
Pelvic incidence-lumbar lordosis	1.044 (0.997–1.095)	0.069		
Cage related parameters				
Height	0.633 (0.360–1.116)	0.114		
Length				
32 mm	Reference			
36 mm	0.592 (0.198–1.775)	0.349		
Insertion side				
Right	Reference			
Left	0.636 (0.213–1.903)	0.419		
X	1.018 (0.931–1.114)	0.692		
Y	1.096 (1.008–1.191)	0.032	1.22 (1.06–1.41)	0.007
Transverse angle	0.986 (0.949–1.024)	0.454		

HDL, herniated lumbar disc; CI, confidence interval.

listhesis and stenosis with unilateral facetectomy, and an increase in SL is thus limited in MIS-TLIF patients. However, McMordie, et al.,[21] who studied the outcomes of MIS-TLIF with lordotic cages, reported that SL increased postoperatively. Changes in SL after MIS-TLIF were significantly associated with preoperative SL. When preoperative SL was small, postoperative SL was likely to increase. Berlin, et al.[30] reported in their study of 121 patients who underwent conventional TLIF that postoperative SL correction at L4/5 was significantly associated with preoperative SL. Frequency distribution analysis showed that postoperative SL of L4/5 is likely to decrease if a patient's preoperative SL is more than 23° and that preoperative SL less than 15° is likely to increase, which is consistent with our conclusion. However, some studies have reported opposing results. In their systemic review, Carlson, et al.[31] reported that a larger preoperative SL was correlated with a larger postoperative SL. We suspect that the inconsistent conclusions on preoperative SL may stem from different operation techniques: we included cage position in analysis to provide more accuracy. However, further study is needed to investigate the role of preoperative SL.

Changes in SL after surgery were significantly associated

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with cage position. The more anteriorly the cage is located, the more likely it becomes that postoperative SL will increase. This is in line with Carlson, et al.[31] who reported that an anterior position of the cage resulted in larger postoperative SL. Lovecchio, et al.[19] also reported that SL increased more following ALIF than after TLIF or LLIF, and they thus concluded that cage position was the only factor influencing SL change after MIS-TLIF. We also found that the Yc axis of the cage was associated with SL, with an anterior cage position correlating with an increase in SL after MIS-TLIF. Notwithstanding, our results should be applied cautiously in clinical situations because an anterior position for the cage sometimes does not result in an SL increase after surgery if preoperative SL and PL are large (Fig. 4). On the other hand, if preoperative SL and PL are small, surgery can produce an SL increase, even if the cage is not positioned anteriorly enough (Fig. 5). Changes in SL after surgery were significantly associated with preoperative PL, with small preoperative PL values correlating with increases in postoperative SL. Lafage, et al.[32] also reported that in adult spinal deformity patients with flat proximal lordosis (smaller PL), PL increased postoperatively, and DL showed no change. We also found that DL before and after surgery did not differ significantly. Pesenti, et al.[33] reported that, unlike PL, which moves to compensate for sagittal balance, DL, which accounts 2/3 of the total LL, is invariable. The only way to increase SL during MIS-TLIF, it appears, is to position the cage as forward as possible. If the goal of surgery is to create large SL and if a patient's preoperative SL and PL are too large, other surgeries, such as ALIF, should be considered instead of MIS-TLIF.

In this study, postoperative SL was significantly associated with the index level of surgery. MIS-TLIF was more likely to increase postoperative SL at L4/5 than at L3/4 in our study population. This is in line with the study by Ricciardi, et al.[34] who reported that TLIF changed SL more at L4/5 than at L3/4. However, we found no research results explaining why TLIF at L4/5 affects SL more than at L3/4. Bernhardt, et al.[35] reported in their radiologic study of 102 normal subjects that lumbar SL gradually increased at each level caudally to the sacrum. We suspect that both SL and other conditions may undergird this result. Further study, comparing L4/5 with L5/S1 would shed light on this. Degenerative spondylolisthesis commonly occurs at L4/5, rather than L3/4, while spondylolytic spondylolisthesis commonly occurs at L5/S1.[36-38] However, diagnosis has no significant correlation between postoperative SL changes as seen in Table 1. Furthermore, although the increased SL group had more L4/5 patients than L3/4 patients (94.1% vs. 5.9%), the decreased group also had more L4/5 patients (71.4%) than L3/4 patients (28.6%). It is likely that each patient's apex of lordosis is unique and that the effects of cage insertion on PL and DL also differ by patient, such that surgical level is not significantly related to postoperative SL changes.

Our study has some limitations. First, as Le Huec, et al.[23] pre-

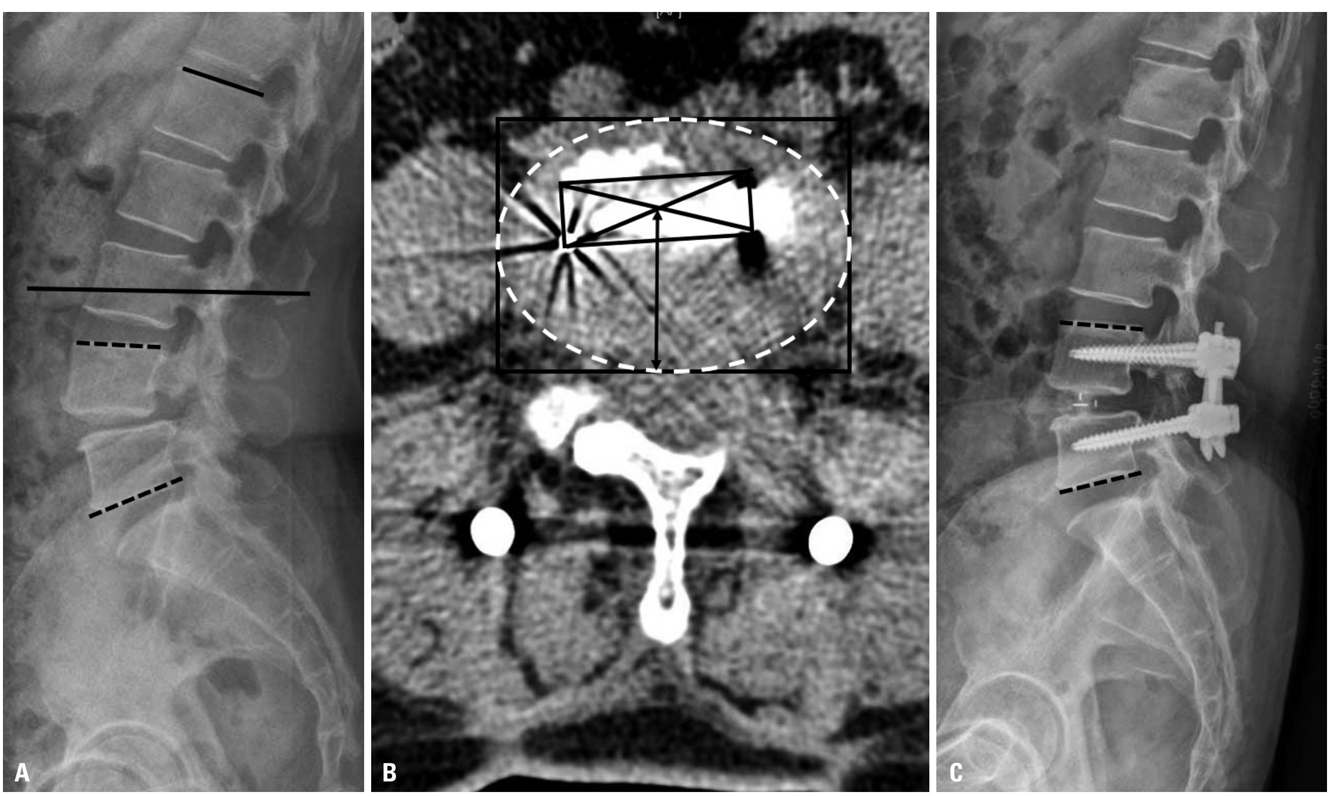

Fig. 4. Patient with decreased segmental lordosis after surgery even though the cage was positioned anteriorly. This patient had large preoperative segmental lordosis (black dotted line, 26.6°) and proximal lordosis (black line, 17.7°) (A). Although the cage was positioned anteriorly (black arrow, 67.4%) in the axial CT image (B), postoperative segmental lordosis was decreased by 15.8° (black dotted line) on 1-year postoperative X-ray (C).

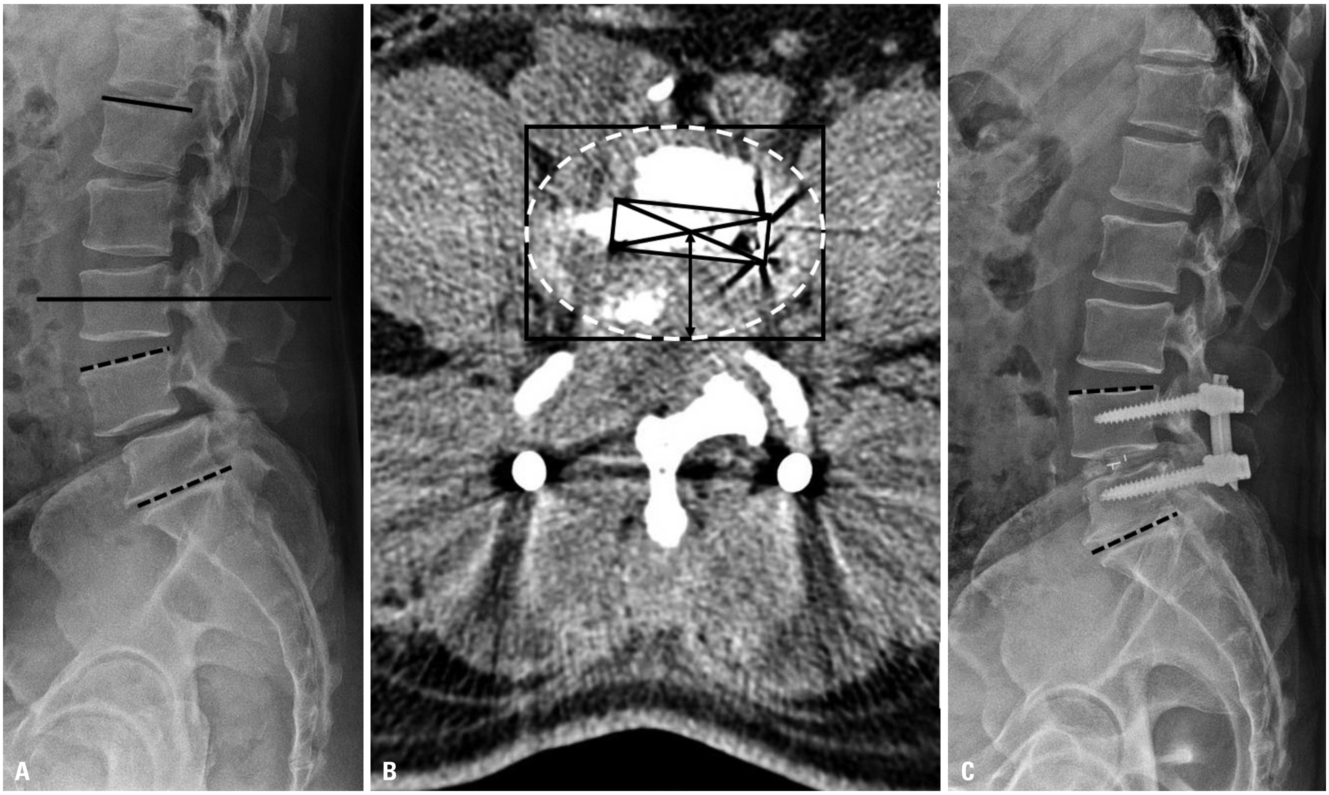

Fig. 5. Patient with increased segmental lordosis after surgery even though the cage was not positioned anteriorly. This patient had small preoperative segmental lordosis (black dotted line, 6.2°) and proximal lordosis (black line, 6.7°) (A). Even though the cage was not positioned anteriorly enough (black arrow, 44.4%) in the axial CT image (B), postoperative segmental lordosis increased by 20.5° (black dotted line) on 1-year postoperative X-ray (C).

sented, according to the formula for calculating a patient's ideal LL from their PI, ideal LL can be achieved by either increasing or decreasing LL, depending on the preoperative LL value. Therefore, the results of our study should be applied in clinical situations according to each patient's preoperative LL and ideal LL, keeping in mind that increasing LL is not always the right answer. In addition, our study does not reflect clinical outcomes, which are as important as radiological outcomes. Second, our study is limited by both our study duration and sample size. To emphasize the effect of operative factors, we compared preoperative x-ray with 1-year postoperative x-ray, thus limiting the assessment of long-term changes. Furthermore, to measure the effect of operative factors as clearly as possible, we controlled our data by excluding unfit data, and this resulted in a small sample size. Despite the fact that all operations were performed by a single surgeon at a single institution, which aids in the consistency of the data, the small sample size is an inherent limitation of this study. Third, the parameters included in this study are related to one another. Among the preoperative radiologic parameters, PI, PT, SS, and LL have close relationships. Furthermore, LL consists of PL and DL; therefore, if either PL or DL is determined, its counterpart is automatically defined. Among cage-related parameters, the X axis, Y axis, and transverse angle are not three independent variables; they are related to the position of the cage. Therefore, although we used multivariable logistic regression to reduce covariance among the variables, those variables still introduce structural errors in the study. Fourth, we confined the index level as L3/4 and L4/5. This was to control the consistency of the data, and our study does not provide information on L5/S1, which is a common level affected by lumbar spondylolisthesis. Further study incorporating level L5/S1 is needed to provide suggestions helpful for spine surgeons in practice. Fifth, the cages used in this study do not have lordotic angle. However, the use of a lordotic cage is growing not only in open lumbar surgery but also in minimal invasive lumbar surgery.[19,39,40] Sixth, global balance has recently been spotlighted as being closely associated with clinical outcomes. We investigated changes in SL, which is a more local change than global balance, because we thought it would be directly affected by operative factors. However, a study of global balance and operative factors would shed more light on how their association affects long-term clinical outcomes. Finally, although parameter measurement was performed by two neurosurgeons and averaged, this study is not free from measurement, inter and intra-observer error. Considering comparison between dichotomized groups of "increased" versus "decreased" SL was the main focus of this study, these errors could swing a patient into one group or another. This is certainly a limitation of our study.

In conclusion, changes in SL after MIS-TLIF are associated with preoperative SL, PL, index level, and the Y axis of the cage position. Smaller preoperative SL and PL, an index level at L4/5 instead of L3/4, and an anterior position for the cage are likely to result in increased SL after MIS-TLIF.

AUTHOR CONTRIBUTIONS

Conceptualization: Bang Sang Hahn and Jeong-Yoon Park. Data curation: Soo-Heon Kim and Bang Sang Hahn. Formal analysis: Soo-Heon Kim and Bang Sang Hahn. Investigation: Soo-Heon Kim and Bang Sang Hahn. Methodology: all authors. Project administration: Jeong-Yoon Park. Resources: Jeong-Yoon Park. Software: Soo-Heon Kim and Bang Sang Hahn. Supervision: Jeong-Yoon Park. Validation: all authors. Visualization: all authors. Writing—original draft: Soo-Heon Kim. Writing—review & editing: all authors. Approval of final manuscript: all authors.

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