Reduction Capacity and Factors Affecting Slip Reduction Using Cortical Bone Trajectory Technique in Transforaminal Lumbar Interbody Fusion for Degenerative Spondylolisthesis

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Abstract:
Introduction: Vertebral slip reduction has been recommended in arthrodesis for lumbar degenerative spondylolisthesis (LDS) to achieve balanced spinal alignment and bone fusion. However, what determines the degree of slip reduction using cortical bone trajectory technique for lumbar pedicle screw insertion is yet to be determined. Thus, in this study, we aim to investigate the slip reduction capacity using cortical bone trajectory (CBT) technique and to identify factors affecting the slip reduction rate.

Methods: This is a retrospective radiological evaluation of prospectively collected patients. In total, 49 consecutive patients who underwent single-level transforaminal lumbar interbody fusion for LDS using the CBT technique were included (mean follow-up: 28.9 months). Firstly, radiological parameters of fused segment including the percentage of anterior vertebral slip (%slip), lordotic angle, and disk height were measured. Then, patient and procedure-related parameters were examined to determine factors related to the slip reduction rate using multiple regression analysis.

Results: The %slip was reduced from 15.0±4.8 to 1.6±2.3% immediately after surgery and 2.2±2.9% at the last follow-up (p<0.01), with a slip reduction rate of 87.5±15.7% and correction loss of 0.6±2.1%. As per multivariate regression analysis, it was found that preoperative %slip (standardized regression coefficient [β]=−0.55, p=0.003) and the depth of screw insertion in the caudal vertebra (β=0.38, p=0.03) were significant independent factors affecting slip reduction rate (adjusted R² =0.29, p=0.008).

Conclusions: To the best of our knowledge, this study is the first to investigate the capacity for and factors affecting slip reduction using the CBT technique for LDS. The CBT technique may be a useful option for achieving slip reduction, and the depth of screw insertion in the caudal vertebra was identified as a significant technical factor to obtain a more significant reduction of slipped vertebra.

Keywords: Cortical bone trajectory, lumbar degenerative spondylolisthesis, slip reduction, lumbar interbody fusion, depth of screw insertion

Introduction

Clinical advantages of spinal fusion for lumbar degenerative spondylolisthesis (LDS) are the decompression of neural elements, stabilization of abnormal mobility, and restoration of balanced alignment. While there exist various valid surgical approaches, including anterior, posterior, lateral, and combined, the role of intentional slip reduction in the operative management of LDS remains controversial. Systematic reviews comparing reduction and arthrodesis in situ have shown comparable surgical outcomes in terms of the operative time, blood loss, patient-reported outcomes, and complication rate, and have concluded that both procedures could be expected to achieve good clinical outcomes. On the contrary, several reports have recommended a reduction procedure to achieve a higher rate of bone fusion and radiological improvement in local alignment. Global sagittal imbalance is a rare condition in LDS; however, minor local imbalance of fused segment may influence surgical outcomes and the potential development of adjacent segment disor-
Generally, a slip reduction maneuver is performed by a ligamentotaxis mechanism in distraction and/or sagittal translation using posterior instrumentation, and the polyaxial pedicle screw system is deemed critical because sagittal realignment relies on screw purchase to apply the necessary reduction force.

In this decade, the cortical bone trajectory (CBT) technique for lumbar pedicle screw insertion has gradually become popular as an alternative to traditional trajectory\(^8,10\). Advantages of CBT are its minimal invasiveness due to laterally directed screw path from a more medial and caudal entry point and rigid screw fixation due to the greater contact with cortical bone within the vertebra, which is especially beneficial for patients with poor bone quality\(^8,10\). On the other hand, the following two points are theoretical concerns regarding the feasibility of slip reduction using the CBT technique for LDS. The first point is the specific angulation of CBT in the sagittal plane. While traditional pedicle screws are placed parallel to the vertebral body, CBT screws are often placed steeply to the vertebral body. It remains unclear whether this unusual trajectory allows the translational force to be applied to the slipped vertebra properly during the reduction maneuver. The second point is related to the angulation of CBT in the axial plane. While the lateral position of the screw head using the traditional trajectory provides enough space for all subsequent procedures, the medial position of CBT screws would then obstruct neural decompression and interbody procedures\(^8,10\). Accordingly, surgeons are obliged to finally place CBT screws and attempt the subsequent reduction maneuver after the interbody cages are placed, which may then interfere with proper slip reduction and cause excessive stress at the bone-screw interface.

Despite the widespread interest and commonality of the CBT technique, to the best of our knowledge, it remains unclear what determines the degree of slip reduction in LDS in detail. Thus, the aim of this present study was to investigate the slip reduction capacity using the CBT technique and to identify the factors affecting the slip reduction rate.

**Materials and Methods**

This research has been approved by the institutional review board of the authors’ affiliated institution. The subjects consisted of 49 consecutive patients who underwent single-level transfemoral lumbar interbody fusion (TLIF) for LDS using the CBT technique by a single surgeon from October 2016 to May 2019. During this period, the CBT technique was performed on all cases with LDS, regardless of the degree of vertebral slip. The indications for spinal fusion were sagittal translation of >3 mm, or segmental angulation of >10° on a flexion-extension radiograph, or posterior widening of the disk space of >5° on a flexion radiograph. Two patients with postoperative infection were excluded. Of the 47 remaining patients, 46 who were followed up for more than 2 years after surgery were enrolled in this study (follow-up rate: 97.9%, mean follow-up: 28.9±5.8 months).

There were 18 males and 28 females, with a mean age of 67.7±10.8 years (range: 48-88 years).

**Surgical procedure**

Through a midline skin incision, the paraspinal muscles were dissected to expose the lateral borders of the pars interarticularis. Firstly, screw pathways were created under fluoroscopic assistance according to a previously described method\(^10\) (Fig. 1A-B). Following posterior decompression with unilateral facetectomy on the dominant side of the neurological symptom and interbody preparation, using a lamina spreader for interbody distraction, interbody cages (one boomerang cage or two rectangular cages) were inserted through a single portal with local bone harvested during the decompression procedure. Lastly, the screw holes were tapped and CBT screws were placed. (Fig. 1C) Each screw was placed uniformly, leaving the screw proud about 3 mm to avoid head of screw impinging against the posterior elements. Slip reduction maneuvers were performed as follows. The rods were locked to the caudal screws, with the initial offset of the rods to the cephalad screw heads reflecting the degree of vertebral slip. Then, the bilateral rods were simultaneously applied to the cephalad screws using a reduction system to generate posterior translational force to the slipped vertebra. During tightening of the cephalad screws, the reduction was achieved by shortening the length of the reduction extender (Fig. 1D). The standard screw size in this present study was 5.5-6 mm in diameter and 40-45 mm in length with the polyaxial head to facilitate rod seating. The screw tip was then placed close to the superior endplate without bicortical penetration. All patients wore a lumbar sacral orthosis for 3 months postoperatively.

**Radiological assessment**

Firstly, the local alignment of the fused segment including the percentage of anterior vertebral slip (%slip), lordotic angle, and disk height was measured in the neutral lateral radiograph preoperatively, 2 weeks postoperatively, and at the last follow-up. Disk height was measured in a distance perpendicular to the middle of the superior endplate of the caudal vertebra. The slip reduction rate (%) was determined as follows: (preoperative %slip-last follow-up %slip)/(preoperative %slip)×100%. The correction loss (%) was determined as follows: (last follow-up %slip−postoperative %slip). Next, the following factors that may be related to the slip reduction rate and correction loss were investigated: (1) age; (2) sex; (3) body mass index; (4) bone mineral density (BMD); (5) spinal level; (6) preoperative vertebral slip; (7) intervertebral mobility, sagittal translation (%), and angulation (°) of the corresponding segment on flexion and extension radiographs; (8) pelvic incidence; (9) sagittal inclination, the angle between the superior endplate of the slipped vertebra with the horizontal line; (10) cage shape, boomerang or rectangular; (11) cage material, titanium or titanium-coated polyether-ether-ketone; (12) cage lordotic angle; (13) cage position; (14) amount of lift up of the disk space, (cage...
Figure 1. Surgical procedure.
A and B: screw paths were created before posterior decompression and marked with L-shaped wires.
C: placement of an interbody cage before screw insertion.
D: reduction of vertebral slip using the pedicle screw system.

height-preoperative disk height); (15) screw diameter; (16) screw length; and (17) depth of the screw in the vertebral body (%depth). BMD was measured in Hounsfield units (HU) of each vertebral body using a protocol described by Schreiber et al. and HU from the cephalad and caudal vertebrae were averaged\textsuperscript{11}. The cage position was categorized into two groups based on whether the middle of the cage was anterior to half of the caudal vertebra in the sagittal plane. The %depth was then defined as the ratio of the mean screw length within the vertebral body to the anteroposterior diameter of the vertebral body in the axial plane using a postoperative computed tomography (CT) image obtained immediately after surgery\textsuperscript{12,13} (Fig. 2).

Lastly, for secondary outcomes, screw loosening and bone fusion rates were evaluated using X-ray or CT at the last follow-up. Screw loosening was defined as a radiolucency >1 mm around the screw. Bone fusion was defined as the presence of a continuous fusion mass between the vertebral bodies and absence of the following: motion of fusion segment >3° and screw loosening\textsuperscript{13,14}.

Statistical analysis

Categorical and continuous variables are presented as numbers and mean±standard deviation, respectively. The differences of radiological parameters were compared using repeated-measures analysis of variance and Tukey’s significant difference multiple comparison tests. To identify the independent factors affecting the slip reduction rate and correction loss, multiple regression analysis was performed using a forward and backward stepwise procedure with inclusion and retention criteria set at 0.20. JMP version 14 (SAS, Cary, NC) was used for all analyses with a significance level of p<0.05.

Results

The details of patient and procedure-related characteristics are summarized in Table 1. The mean preoperative %slip was 15.0±4.8%, including 36 of 46 patients with Grade I and 10 patients with Grade II according to the Meyerding criteria\textsuperscript{15}. The %slip was reduced to 1.6±2.3% immediately after surgery and 2.2±2.9% at the last follow-up (p<0.01), with a slip reduction rate of 87.5±15.7% and correction loss of 0.6±2.1% (Fig. 3A). The lordotic angle of the fused segment was noted to increase from 5.0±4.9° preoperatively to 9.2±3.4° postoperatively, and this was maintained until the last follow-up. (Fig. 3B) Also, the disk height increased from 8.1±2.5 to 9.7±1.6 mm postoperatively, and remained the same at the last follow-up (Fig. 3C).

Multivariate regression analysis revealed that preoperative %slip (standardized regression coefficient [β]=−0.55, p=0.003) and %depth in the caudal vertebra (β=0.38, p=0.03) were significant independent factors affecting the slip reduction rate (adjusted R²=0.29, p=0.008) (Table 2). No multicollinearity was observed between the independent variables. No significant factor affecting correction loss was identified.
Figure 2. Percent depth.
The %depth was defined as the ratio of the screw length within the vertebral body (A), not including the screw length outside the vertebra by screw perforation, to the anteroposterior diameter of the vertebral body (B) in the axial place.

Table 1. Patient and Procedure-related Characteristics.

| Parameters | Age (years) | Sex (M:F) | Body mass index (kg/m²) | Bone mineral density (HU) | Level | Vertebral slip (%) | Intervertebral mobility | Pelvic incidence (°) | Sagittal inclination (°) | Cage shape (boomerang/rectangular) | Cage material (T:TP) | Cage lordotic angle (°) | Cage position (anterior/posterior) | Lift up (mm) | Screw diameter (mm) | Screw length (mm) | %depth (%) |
|------------|-------------|-----------|-------------------------|--------------------------|-------|---------------------|------------------------|-----------------------|------------------------|------------------------------------|-----------------|------------------------|-----------------------------|-------------|-------------------|-------------------|-----------|
|            | 67.7±10.8   | 18:28     | 24.5±3.5                | 136.5±54.3               |       | 15.0±4.8            | 7.5±3.6                | 49.6±3.8              | 8.2±9.3                | 29:17                              | 5:41            | 7.0±2.3                | 39:7                         | 1.3±1.9    | 5.8±0.2          | 41.3±2.6         | 54.5±8.4   |

T, titanium; TP, titanium-coated polyether-ether-ketone.

Screw loosening was observed in 2.2% of patients (1 of 46), and bone fusion was achieved in 93.5% of patients (43 of 46) at the last follow-up. There were no cases requiring revision surgery due to screw loosening or pseudoarthrosis.

Discussion

The goals of slip reduction are to achieve physiological spinal alignment, an optimal neural environment, and larger fusion bed between the vertebrae. To the best of our knowledge, this present study is the first to investigate the factors affecting slip reduction using the CBT technique. The reduction rate of vertebral slip was 87.5±15.7% with a low incidence of screw loosening, and preoperative vertebral slip and screw insertion depth in the caudal vertebra were identified as factors contributing to the slip reduction rate.

Pedicle screws are known to play a crucial role in achieving spinal correction and maintaining spinal alignment; however, the reduction maneuver may theoretically load excessive stress on the bone-screw interface, which could then lead to screw loosening, loss of correction, and delayed bone fusion. Because instrumentation failure is the result of a complex combination of factors, the reduction maneuver itself may go unrecognized as a possible cause. This study showed a comparable or superior slip reduction rate to those reported in previous studies (Table 3). One reason for the favorable results may be that the preoperative vertebral slip, which was identified as a factor contributing to the slip reduction rate in this study, was not as large as in other reports. Moreover, the following two biomechanical characteristics of the CBT screw were potentially associated with this result. One is that CBT screws can achieve rigid fixation at the bone-screw interface because of the denseness of the cortical tract, which may withstand reduction force and improve translational control of the slipped vertebra. The other is that sagittal angulation of CBT screws can produce a buttress effect against reduction force applied parallel to the vertebral body, not along the screw axis (Fig. 4A). On the contrary, when using the traditional trajectory screw, reduction force is applied along the screw axis, which translates into a pullout force, leading to instrumentation failure as well as loss of slip reduction (Fig. 4B). Ninomiya et al. performed a retrospective study to compare the radiological outcomes between CBT and traditional trajectory techniques in posterior lumbar interbody fusion for LDS, and reported that the CBT technique (71.2%) demonstrated a higher slip reduction rate than the traditional trajectory technique (60.6%). The biomechanical advantages of CBT mentioned above might improve the reduction capacity and maintain the correction.

In terms of factors related to slip reduction, little is known about what determines the degree of reduction during arthrodesis for LDS. Chung et al. investigated slip reduction and associated parameters in oblique lumbar interbody fusion combined with posterior screw fixation. They revealed that three factors significantly affected slip reduction: age <65 years, anterior cage placement, and resection of the inferior facet. Their findings were based on single regression analysis, which was different from the multiple regression analysis used in this present study, and our findings were not consistent with theirs. In this study, larger preoperative
vertebral slip was associated with a lower rate of slip reduction. Theoretically, larger vertebral slip necessitates a greater correction force for vertebral reduction. The correction force is created by the initial locking between the rods and caudal screws and acts to draw back the cephalad screws; however, the force is not directly or fully transmitted to the slipped vertebra and is reduced due to pivoting micro-mobility in the sagittal plane at the screw shaft-head connection of polyaxial screws and the bone-screw interface. This mechanism may lead to surgeons losing control of the reduction maneuver, especially in cases with large vertebral slip. An interesting finding of this study was that deeper screw insertion in the caudal vertebra was identified as the only technical factor contributing to slip reduction (Fig. 5). Previous studies examining the effect of the CBT screw depth in the vertebra demonstrated the biomechanical superiority of longer and deeper screws by achieving enhanced cortical purchase and better load-sharing within the vertebral body. From this aspect, both the cephalad and caudal screws need to be placed deeply, but the caudal screws, in particular, served as a fixed point during the reduction maneuver, and deeper screw placement could improve translational control of the slipped vertebra. In this study, the mean %depth of the caudal vertebra was about 7% greater than that of the cephalad vertebra, although the difference was insignificant. We speculate that this was due to the fact that the entry point of the cephalad vertebra was made slightly inferior to avoid the adjacent facet, resulting in a slightly shorter trajectory.

The findings of this present study have practical implications because there has been no consensus on the reduction procedure using the CBT technique for LDS. Firstly, the caudal screw of the corresponding segment should be placed sufficiently deeper into the vertebral body to act as a rigid anchor during the reduction maneuver. Although the optimal depth of screw insertion for slip reduction has yet to be elu-

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**Table 2.** Multivariate Regression Analysis with Slip Reduction Rate.

| Parameters                  | B     | Standard error | t value | P     | β     | VIF |
|-----------------------------|-------|----------------|---------|-------|-------|-----|
| Vertebral slip (%)          | −1.79 | 0.56           | −3.21   | 0.003 | −0.55 | 1.15|
| Caudal %depth               | 0.66  | 0.30           | 2.20    | 0.03  | 0.38  | 1.15|

B, unstandardized regression coefficient; β, standardized regression coefficient; VIF, variance inflation factor.

**Table 3.** Slip Reduction in Lumbar Interbody Fusion.

| Year | First author | Screw trajectory | Fusion technique | Number (cases) | Vertebral slip (mean, %) | Reduction rate |
|------|--------------|------------------|------------------|----------------|--------------------------|----------------|
|      |              |                  |                  |                | Pre | Post |                 |
| 2013 | Lian         | TT               | PLIF             | 36             | 18.3 | 3.1  | 83.1%           |
| 2015 | Rao          | none             | ALIF             | 27             | 14.8 | 9.4  | 36.5%           |
| 2016 | Ninomiya     | TT               | PLIF             | 10             | 12.7 | 5.0  | 60.6%           |
|      |              | CBT              | PLIF             | 11             | 11.1 | 3.2  | 71.2%           |
|      |              | TT               | PLIF             | 11             | 11.1 | 3.2  | 71.2%           |
|      |              | CBT              | PLIF             | 41             | 18.2 | 10.1 | 44.5%           |
| 2019 | Ko           | TT               | TLIF             | 39             | 20.0 | 4.6  | 77.0%           |
|      |              | TT               | LLIF             | 41             | 18.2 | 10.1 | 44.5%           |
| 2020 | Ishii        | TT               | LLIF             | 52             | 24.0 | 4.3  | 82.1%           |
|      |              | TT               | LLIF             | 52             | 24.0 | 4.3  | 82.1%           |
|      |              | TT               | LLIF             | 52             | 24.0 | 4.3  | 82.1%           |
| 2021 | Mori         | TT               | TLIF             | 52             | 18.2 | 4.7  | 74.2%           |
|      |              | CBT              | TLIF             | 46             | 15.0 | 2.2  | 87.5%           |
| 2021 | Pan          | TT               | TLIF             | 52             | 18.2 | 4.7  | 74.2%           |
|      |              | CBT              | TLIF             | 52             | 18.2 | 4.7  | 74.2%           |

TT, traditional trajectory; CBT, cortical bone trajectory.
Figure 4. Lateral fluoroscopic images of the cortical bone trajectory (A) and traditional trajectory techniques (B) showing reduction force applied parallel to the vertebral body. White arrows indicate reduction force on the cephalad screw head, whereas black arrows indicate buttress effect of CBT screws.

Figure 5. Representative case. A 64-year-old female. Screw depth in the caudal vertebral body of 70% with slip reduction rate of 100% [preoperative slip: 37% (A), last follow-up slip: 0% (B)].

cidated from a clinical and biomechanical point of view, the ideal CBT should start from the pars interarticularis, pass the inferior border of the pedicle, and end around the middle of the vertebral endplate\(^{10,13}\). When surgeons pursue a deeper screw trajectory, the trajectory may become close to the pedicle axis in the sagittal plane using less steep trajectory. However, this trajectory could damage the adjacent facet and fail to appropriately contact the cortical bone concentrated between the pars interarticularis and inferior part of the pedicle\(^{10}\). Because of the novelty and narrow bone corridor of CBT, it is technically demanding to achieve both a longer trajectory and appropriate contact with cortical bone. The application of intraoperative fluoroscopy and modern technologies such as a navigation system, robotic system, and patient-specific template guide is effective to enhance screw placement accuracy\(^{27,28}\). Secondly, in cases with larger preoperative vertebral slip, wider neural decompression is necessary because indirect decompression following complete slip reduction may not be expected. Resection of the bilateral facet joint becomes a valid option to achieve segmental mobility, as Chung et al. reported\(^{22}\).

This study has several limitations of the present study that should be noted. First, most of the enrolled cases were Mer- erding Grade I slip with vertebral slip of 15.0±4.8%, further radiological evaluation is necessary to investigate the reduction capacity using the CBT technique in cases with greater vertebral slip. Second, this study was a single-surgeon experience with a relatively small number of cases and lacked direct comparison with other reduction techniques. Third, we focused on only the radiological outcomes. Thus, additional long-term comprehensive studies, including clinical outcomes, global alignment changes, and the incidence of
adjacent segment disorders, are needed to elucidate the significance of slip reduction for LDS. In conclusion, to the best of our knowledge, this study is the first to investigate the capacity for and factors affecting slip reduction using the CBT technique in TLIF for LDS. The CBT technique may be a useful option for achieving slip reduction, and the depth of screw insertion in the caudal vertebra was a significant technical factor to obtain greater reduction of slipped vertebra.

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(1) Conception and design: Keitaro Matsukawa
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Ethical Approval and Informed Consent: This study was performed after obtaining approval from our institutional review board the Research Ethics Committee of Murayama Medical Center (ID: 12-10). Informed consent was obtained from all individual participants included in the study.

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