



L5 pedicle subtraction osteotomy maintains good radiological and clinical outcomes in elderly patients with a rigid kyphosis deformity: a more than 2-year follow-up report

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Abstract

Purpose L5 pedicle subtraction osteotomy (PSO) is a demanding technique; thus, PSOs are usually performed at the L3/L4 level to correct the lack of lumbar lordosis. Mid- to long-term improvements in clinical outcomes after L5 PSO are unknown. We aimed to determine the efficacy and safety of L5 PSO for rigid kyphosis deformities.

Methods We retrospectively reviewed the records of 57 patients with a rigid kyphosis deformity (mean age: 68 years) who underwent extensive corrective surgery incorporating PSO with a > 2-year follow-up. Radiographic parameters, postoperative complication rates, and the Oswestry Disability Index (ODI) scores were compared in the L5, L4, and L1-3 PSO groups preoperatively and at 1, 2, and 5 years postoperatively.

Results There were 12, 25, and 20 patients in the L5, L4, and L1-3 PSO groups, respectively. Significant between-group differences were found in preoperative L4–S1 lordosis (L5:L4:L1-3 PSO groups = $-8.9^\circ:8.9^\circ:16.2^\circ$, $P < 0.001$). The surgeries improved the postoperative spinopelvic alignment (similar in all groups). There was no significant between-group difference in the postoperative complication rate; no irreversible complications occurred. In the L5 PSO group, there was one case of a common iliac vein injury. The ODI scores improved postoperatively in all groups; this was maintained for 5 years postoperatively.

Conclusion L5 PSO for L4-5/L5 kyphosis deformities resulted in adequate correction and ODI improvement, which were maintained up to 5 years postoperatively. The surgical invasiveness, complication rates, and long-term prognosis associated with L5 PSO were similar to those of PSOs performed at other levels.

Keywords Adult spinal deformity · Correction surgery · Pedicle subtraction osteotomy · Complication · Clinical outcome

Introduction

Rigid lumbosacral kyphotic deformity with sagittal malalignment is caused by severe degenerative changes, vertebral fractures, post-laminectomy, and neuromuscular diseases [1]. Three-column osteotomies, including pedicle subtraction osteotomy (PSO) and vertebral column resection, can correct rigid kyphotic deformities with fixed global malalignment [2, 3] and can effectively restore significant lumbar lordosis (LL) in patients with a rigid kyphosis deformity [4, 5]. PSO is usually performed at the L3/L4 level, showing improvements in radiographic parameters and clinical outcomes with acceptable postoperative complication rates [5].

Kyphosis deformities induce various symptoms, such as abnormal posture, walking dysfunction, fatigue-induced

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lumbago, and gastroesophageal reflux, which may indicate the need for correction surgery [6, 7]. The goals of correction surgery are to improve global malalignment, prevent kyphosis deformity progression, and relieve pain for improving health-related quality of life (HRQOL). The HRQOL clinical outcomes of patients with spinal deformities following correction surgery are primarily evaluated using the Scoliosis Research Society (SRS)-22 or Oswestry Disability Index (ODI) [8, 9].

Patients with L4–5/L5 rigid kyphosis deformities have more severe kyphosis deformities and global spinopelvic malalignment than those with L2/L3 kyphosis deformities. L5 PSO may be needed to correct severe malalignment due to L4–5/L5 rigid kyphosis deformities by restoring anatomical L4–S1 lordosis [2]. L5 PSO requires sufficient lateral vertebral body dissection to prevent intraoperative main vascular injury, which is challenging because of the shallow vertebra with significant surrounding vasculature [2]. Furthermore, the rates of pseudoarthrosis at the osteotomy level and instrumentation failure may increase due to the reduction in distal construct strength compared to that with L1–4 PSO [1, 2]. Mid- to long-term studies on L5 PSOs for rigid kyphosis correction are rare. To the best of our knowledge, this is the first 2–5-year follow-up longitudinal study of the radiological and clinical outcomes following L5 PSO. We aimed to compare spinopelvic parameters and clinical outcomes between L5, L4, and L1–3 PSOs for the correction of rigid kyphosis deformities of multiple aetiologies and to investigate the mid-term effects of PSO on improvements in spinopelvic alignment and clinical outcomes.

Materials and methods

We hypothesised that L5 PSO restores proper L4–S1 lordosis and improves global alignment and HRQOL. Therefore, it can be considered relatively safe and reliable for rigid kyphosis correction surgery.

Institutional review board approval

The study protocol was approved by the Institutional Review Board of our university hospital (No. 14-306) and adhered to the Declaration of Helsinki.

Patient selection and study measures

Data were retrospectively reviewed from a database of adult spinal deformity (ASD) surgeries at a single centre. We investigated 336 consecutive patients with ASDs who underwent spinal corrective fusion surgery in 2010–2017 (Fig. 1). Inclusion criteria were (1) age ≥ 40 years, (2) ≥ 2 -year follow-up, and (3) informed consent to participate. Exclusion

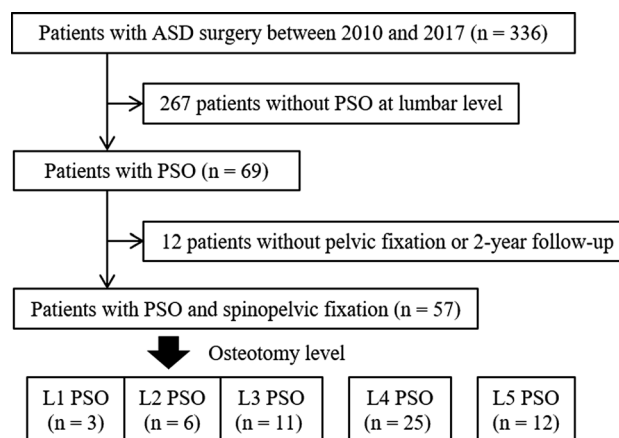


Fig. 1 Study design

criteria were (1) no PSO at the lumbar level, (2) no spinopelvic fixation, and (3) insufficient assessment of radiographic parameters or HRQOL preoperatively and at 2 years postoperatively. Finally, 57 PSO cases were enrolled (mean age 67.7 years; 11 men, 46 women) (Table 1). ASD was defined as the presence of at least one of the following indicators: degenerative or idiopathic scoliosis with spinal curvature $> 20^\circ$ in the coronal plane, C7 sagittal vertical axis (SVA) > 50 mm, pelvic tilt (PT) $> 25^\circ$, and T5–T12 thoracic kyphosis (TK) $> 60^\circ$. Altogether, 39 patients (68%) were followed-up over 5 years.

Variables, data sources, and bias

Patient characteristics and medical and demographic details were obtained from medical records. Age, sex, body mass index, alcohol intake, smoking status, American Society of Anesthesiologists classification, presence of two-stage surgery, upper instrumented vertebra, number of fused vertebral segments, screw insertions, rods, posterior lumbar interbody fusion, length of surgery, and estimated blood loss (EBL) were recorded. We defined upper instrumented vertebra (UIV) levels as follows: T1 vertebral body = 1, T2 = 2, and T3 = 3...T12 = 12. The measured radiographic parameters were cervical lordosis (CL); TK; L1–S1 LL, and L4–S1 lordosis (in L4 PSO cases, the L4–S1 lordosis was measured between L3 caudal and S1 cranial endplates); sacral slope (SS); PT; pelvic incidence (PI); T1 slope; C7 sagittal vertical axis (SVA); T1 pelvic angle (TPA); proximal junctional sagittal angle; C7 plumb line and centre sacral vertical line (C7-CSVL); and Cobb angle preoperatively and at 6 months, 1, 2, and 5 years postoperatively. We evaluated in-hospital perioperative complications, including postoperative motor deficit, major vessel injury, surgical site infection (SSI), pneumonia, urinary tract infection, cardiac complications, postoperative haematoma, deep venous thrombosis (DVT),

Table 1 Comparison of baseline characteristic and surgical data in the L5 pedicle subtraction osteotomy (PSO), L4 PSO and L1-3 PSO groups

Variable	L5 PSO group (n = 12)	L4 PSO group (n = 25)	L1-3 PSO group (n = 20)	P value (ANOVA)	P value (Tukey)
Age (years)	67.5 ± 10.0	69.4 ± 6.2	65.7 ± 11.2	0.386	–
Female sex	11 (91.7%)	22 (88.0%)	13 (65.0%)	0.218	–
Height (cm)	147.2 ± 8.7	150.7 ± 9.3	154.9 ± 13.4	0.147	–
Body weight (kg)	52.0 ± 14.2	53.7 ± 9.1	60.5 ± 15.0	0.109	–
Body mass index (kg/m ²)	24.0 ± 6.4	23.7 ± 3.7	25.0 ± 3.4	0.595	–
Alcohol consumer	0 (0%)	2 (8.0%)	5 (25.0%)	0.248	–
Smoker	1 (8.3%)	2 (8.0%)	5 (25.0%)	0.461	–
ASA classification score	2.0 ± 0.4	1.9 ± 0.4	2.0 ± 0.4	0.697	–
<i>Condition</i>					
Degenerative kyphosis	3 (25.0%)	9 (36.0%)	12 (70.0%)	0.230	–
Iatrogenic flat back	4 (33.3%)	6 (24.0%)	3 (15.0%)	0.742	–
Neuromuscular disease	2 (16.7%)	3 (12.0%)	2 (10.0%)	0.999	–
Degenerative kyphoscoliosis	1 (8.3%)	4 (16.0%)	1 (5.0%)	0.773	–
Kyphosis due to vertebral fracture	2 (16.7%)	3 (12.0%)	0 (%)	0.538	–
Ankylosing spondylitis	0 (0%)	0 (0%)	1 (5.0%)	0.968	–
Adult idiopathic scoliosis	0 (0%)	0 (0%)	1 (5.0%)	0.968	–
<i>Surgical factors</i>					
Two-stage surgery	0 (0%)	1 (4.0%)	4 (20.0%)	0.292	–
Upper instrumented vertebra	9.5 ± 2.4	9.0 ± 2.6	8.9 ± 2.3	0.554	–
Number of fused vertebral segments	8.6 ± 2.0	8.8 ± 1.6	9.2 ± 1.6	0.556	–
Number of screw insertions	20.3 ± 3.6	18.3 ± 2.9	19.7 ± 2.3	0.114	–
Number of rods	2.8 ± 0.9	2.7 ± 0.9	2.8 ± 0.9	0.857	–
Number of PLIF	1.9 ± 1.4	1.7 ± 0.9	1.5 ± 1.2	0.673	–
Length of surgery (min)	473 ± 116	433 ± 62	463 ± 96	0.348	–
Estimated blood loss (ml)	2450 ± 1180	1890 ± 900	1680 ± 1010	0.114	–

Values expressed as mean ± SD or number (percentage). Multiple comparison a: L5 PSO versus L4 PSO, b: L5 PSO versus L1-3 PSO, c: L4PSO versus L1-3 PSO. *statistically significant difference

ASA american society of anesthesiologists, *PLIF* posterior lumbar interbody fusion

and pulmonary embolism, as well as instrumentation-related complications, including rod fractures, proximal junctional failure (PJF), pseudoarthrosis at osteotomy site, iliac screw loosening, and iliac screw breakage, until the final follow-up (minimum of 2 years postoperatively). PJF was defined as vertebral fracture of the UIV or implant failure at the UIV and one or two vertebrae above. Screw loosening was defined as a radiolucent area (≥ 1 mm in circumference) around the screw, noted on plain radiographs [10].

Selection of vertebral level osteotomy and grouping

Patients with a rigid kyphosis or wedge-shaped vertebra with a posterior height more than two-thirds of the vertebral body underwent correction surgery with PSO of Schwab grade IV [11]. For better correction and to increase the fusion rate, the disc was systematically removed to obtain bone-to-bone contact post-reduction. The PSO level was selected based on the vertebral body at the kyphosis deformity apex or the

lower vertebral body if the kyphosis deformity apex was located at disc level (typical case presentation; Figs. 2 and 3). L1-4 PSO was performed with a bilateral single iliac screw (Fig. 2b); L5 PSO was performed with bilateral dual iliac screws to secure enough bony anchors (Fig. 3b). Multi-modal intraoperative neuromonitoring was performed routinely, particularly on the nerve roots [12, 13]. According to the PSO level, patients were divided into the L5, L4, and L1-3 PSO groups.

HRQOL assessment

The SRS-22 and ODI scores were investigated preoperatively and at 1, 2, and 5 years postoperatively. ODI is a simple and universal 10-question tool that evaluates the HRQOL of patients with lower-back pain [8]. The SRS-22r is a more comprehensive assessment of patient health spanning five domains: function, pain, self-image, mental health, and satisfaction [9].

Fig. 2 Case 1 A 82-year-old man with rigid L2/3 kyphosis deformity due to degenerative changes (**a, d**). T9 to ilium fusion surgery with L3 posterior subtraction osteotomy and bilateral single iliac screw (**b, e**). The lumbar lordosis (LL) and L4–S1 lordosis improved from 7° and 24° preoperatively to 42° and 34° soon after surgery, respectively (**a, c**)

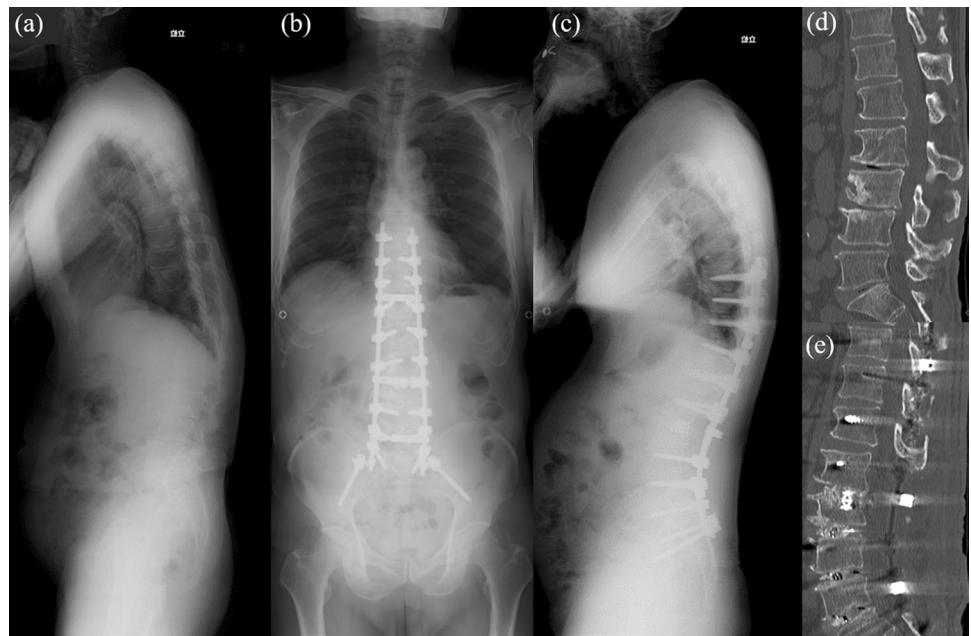


Fig. 3 Case 2 A 72-year-old woman with rigid L5 kyphosis deformity due to iatrogenic flat back (**a, d**). T10 to ilium fusion surgery with L5 posterior subtraction osteotomy and bilateral dual iliac screw (**b, e**). The lumbar lordosis (LL) and L4–S1 lordosis improved from 6° and -9° preoperatively to 60° and 29° soon after surgery, respectively (**a, c**)



Statistical analysis

Categorical variables are expressed as absolute numbers and percentages and normally distributed continuous variables as mean \pm standard deviations. One-way analysis of variance followed by Tukey post hoc and Chi-square tests was used to detect between-group differences. Statistical analyses were conducted using SPSS version 23.0 (IBM, Armonk, NY, USA). $P < 0.05$ was considered significant.

Results

Patient characteristics and surgical and radiographic data

There were 12, 25, and 20 patients in the L5 PSO, L4 PSO, and L1-3 PSO groups, respectively. Baseline characteristics and surgical data did not differ between the groups (Table 1). Regarding radiographic parameters,

significant differences in preoperative L4–S1 lordosis (L5 PSO: L4 PSO: L1–3 PSO groups = -8.9° : 8.9° : 16.2° , $P < 0.001$), preoperative TPA (55.2° : 44.7° : 41.4° , $P = 0.026$), and postoperative Cobb angles (2.7° : 4.5° : 7.9° , $P = 0.037$) were found between the groups (Table 2). Postoperative L4–S1 lordosis did not differ between the groups (L5 PSO: L4 PSO: L1–3 PSO groups = 29.3° : 33.4° : 26.6° , $P = 0.061$), but the correction amount of the L4–S1 lordosis (soon after surgery minus preoperatively) was larger in the L5 PSO group than in the L4 and L1–3 PSO groups (38.2° : 24.5° : 10.5° , $P < 0.001$) (Table 2). Spinal corrective fusion surgeries improved local and global alignment postoperatively in all groups, and the improvements were maintained (Fig. 4).

Peri- and postoperative complications of PSO

Among 63 perioperative complications, all were reversible with appropriate treatment. Perioperative complication rates did not differ among the groups (Table 3).

Five patients with postoperative motor deficits due to tethering of the nerve root experienced transient radiculopathy and paralysis, which resolved spontaneously with conservative treatment. One patient in the L5 PSO group had a common iliac vein injury and was treated by a cardiovascular surgeon. Four patients had SSIs; one patient with pneumonia and two with urinary tract infections were treated with intravenous antibiotics. One patient with a postoperative haematoma underwent immediate removal; the motor deficit improved completely. Five patients with DVTs, including one with a pulmonary embolism, were treated with anticoagulants. Among

Table 2 Comparison of radiographic parameters in the L5 pedicle subtraction osteotomy (PSO), L4 PSO, and L1–3 PSO groups

Variable	L5 PSO group (n = 12)	L4 PSO group (n = 25)	L1–3 PSO group (n = 20)	P value (ANOVA)	P value (Tukey)
<i>Preoperative radiographic parameters</i>					
Cervical lordosis ($^\circ$)	26.0 ± 26.4	21.3 ± 16.0	24.4 ± 20.3	0.773	–
Thoracic kyphosis ($^\circ$)	17.1 ± 16.6	16.6 ± 16.4	20.7 ± 21.5	0.741	–
Lumbar lordosis ($^\circ$)	3.3 ± 27.8	-6.0 ± 21.9	2.9 ± 19.0	0.328	–
L4–S1 lordosis ($^\circ$)	-8.9 ± 12.9	8.9 ± 12.8	16.2 ± 15.8	$< 0.001^{**}$	** ; a, b
Sacral slope ($^\circ$)	23.7 ± 18.9	13.6 ± 10.7	12.3 ± 11.9	0.194	–
Pelvic tilt ($^\circ$)	37.8 ± 15.3	38.3 ± 9.7	35.2 ± 12.3	0.673	–
Pelvic incidence ($^\circ$)	61.5 ± 16.6	51.9 ± 9.5	47.5 ± 13.7	0.070	–
PI–LL ($^\circ$)	58.3 ± 20.8	57.8 ± 22.3	44.6 ± 22.6	0.101	–
T1 slope ($^\circ$)	45.1 ± 20.0	33.4 ± 16.4	40.0 ± 17.6	0.171	–
Sagittal vertical axis (mm)	214.4 ± 83.7	167.4 ± 102.3	169.6 ± 106.9	0.376	–
T1 pelvic angle ($^\circ$)	55.2 ± 13.4	44.7 ± 12.9	41.4 ± 14.5	0.026^*	* ; b
PJA ($^\circ$)	3.9 ± 7.1	4.4 ± 6.5	4.4 ± 6.6	0.976	–
C7–CSVL (mm)	23.4 ± 22.7	24.2 ± 25.0	23.3 ± 18.0	0.989	–
Cobb angle ($^\circ$)	9.5 ± 12.1	10.4 ± 9.0	21.8 ± 19.6	0.067	–
<i>Parameters soon after surgery</i>					
Cervical lordosis ($^\circ$)	16.5 ± 13.8	15.2 ± 13.3	15.2 ± 16.7	0.963	–
Thoracic kyphosis ($^\circ$)	29.8 ± 10.4	32.0 ± 10.1	34.0 ± 13.4	0.605	–
Lumbar lordosis ($^\circ$)	45.7 ± 14.7	41.2 ± 10.4	36.6 ± 13.6	0.143	–
L4–S1 lordosis ($^\circ$)	29.3 ± 8.6	33.4 ± 8.5	26.6 ± 11.0	0.061	–
Sacral slope ($^\circ$)	35.5 ± 14.9	29.8 ± 8.2	27.4 ± 9.2	0.101	–
Pelvic tilt ($^\circ$)	26.7 ± 12.1	21.2 ± 8.0	19.7 ± 9.3	0.125	–
PI–LL ($^\circ$)	16.5 ± 13.2	9.8 ± 11.0	11.0 ± 15.8	0.355	–
T1 slope ($^\circ$)	28.5 ± 8.0	23.6 ± 10.6	31.2 ± 16.0	0.130	–
Sagittal vertical axis (mm)	38.0 ± 46.1	40.2 ± 32.1	64.3 ± 79.9	0.443	–
T1 pelvic angle ($^\circ$)	23.1 ± 12.0	18.8 ± 7.6	20.8 ± 10.2	0.491	–
PJA ($^\circ$)	9.5 ± 6.2	10.5 ± 8.6	13.1 ± 7.0	0.378	–
C7–CSVL (mm)	13.1 ± 14.7	17.8 ± 24.1	21.1 ± 21.2	0.599	–
Cobb angle ($^\circ$)	2.7 ± 4.6	4.5 ± 4.9	7.9 ± 6.7	0.037^*	* ; b

Values expressed as mean \pm SD. Multiple comparison a: L5 PSO versus L4 PSO, b: L5 PSO versus L1–3 PSO, c: L4PSO versus L1–3 PSO. *Statistically significant difference

PI–LL pelvic incidence–lumbar lordosis, PJA proximal junction sagittal Cobb angle, C7–CSVL C7 plum line and the centre sacral vertical line

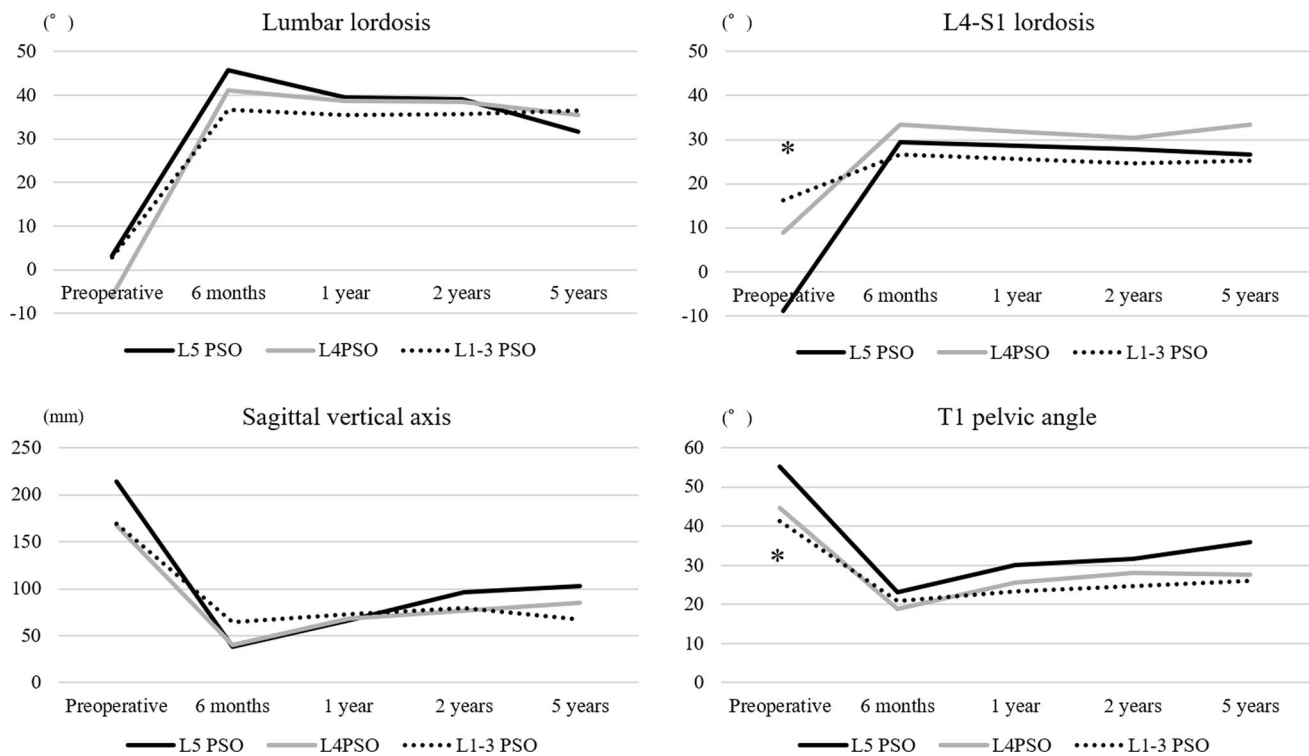


Fig. 4 Preoperative and postoperative changes in the radiographic parameters between L5, L4, and L1-3 pedicle subtraction osteotomy (PSO) groups, *statistically significant difference. Eight cases with

L5 PSO, 18 cases with L4 PSO, and 13 cases with L1-3 PSO who were followed more than 5 years

23 patients with rod fractures, 15 underwent rod replacement surgery, and 8 received conservative treatment because the pain improved without correction loss. Among nine patients with PJF, five underwent revision surgery and four received conservative treatment because the pain improved without correction loss of global alignment. No revision surgery was needed in one patient with pseudoarthrosis and eight patients with iliac screw loosening.

SRS-22r and ODI score changes (Table 4)

Of the 57 PSO patients, 39 were followed up for > 5 years (L5 PSO:L4 PSO:L1-3 PSO groups = 8:18:13). Preoperative SRS-22r domain scores did not differ between groups. SRS-22r scores for all domains improved postoperatively in all groups and were maintained. There was a significant between-group difference in

preoperative ODI scores (L5 PSO:L4 PSO:L1-3 PSO groups = 56.3:47.3:38.9, $P=0.019$). ODI scores improved postoperatively in all groups; the improvements were maintained.

Discussion

This study showed that L5 PSO for rigid kyphosis deformities with sagittal malalignment is challenging but needed to correct severe malalignment due to L4-5 or L5 rigid kyphosis deformities by restoring proper L4–S1 lordosis. Length of surgery, EBL, and postoperative complication rates did not differ significantly between L5 PSO, L4 PSO, and L1-3 PSO groups. Surgical risks did not differ according to the osteotomy level. Although patients with L4-5 or L5 rigid kyphosis deformities had more severe local kyphosis

Table 3 Incidence of postoperative complications in the L5 pedicle subtraction osteotomy (PSO), L4 PSO, and L1-3 PSO groups

Variable	L5 PSO group (n = 12)	L4 PSO group (n = 25)	L1-3 PSO group (n = 20)	P value (Chi-square)
<i>Intraoperative complication</i>				
Postoperative motor deficit	1 (8.3%)	2 (8.0%)	2 (10.0%)	1.000
Common iliac vein injury	1 (8.3%)	0 (0%)	0 (0%)	0.817
Any intraoperative complication	2 (16.7%)	2 (8.0%)	2 (10.0%)	0.972
<i>Perioperative complication in hospital</i>				
Surgical site infection	2 (16.7%)	2 (8.0%)	0 (0%)	0.555
Pneumoniae	0 (0%)	1 (4.0%)	0 (0%)	0.996
Urinary tract infection	0 (0%)	1 (4.0%)	1 (5.0%)	1.000
Cardiac complications	0 (0%)	1 (4.0%)	0 (0%)	0.996
Gastrointestinal complications	2 (16.7%)	1 (4.0%)	0 (0%)	0.457
Postoperative hematoma	0 (0%)	1 (4.0%)	0 (0%)	0.996
Deep venous thrombosis	2 (16.7%)	3 (12.0%)	0 (0%)	0.538
Pulmonary embolism	1 (8.3%)	0 (0%)	0 (0%)	0.817
Any postoperative complication	5 (41.7%)	7 (28.0%)	1 (5.0%)	0.118
<i>Postoperative complication related to instrumentation</i>				
Rod fractures	3 (25.0%)	14 (56.0%)	6 (30.0%)	0.215
Proximal junctional failure	1 (8.3%)	4 (16.0%)	4 (20.0%)	0.932
Pseudoarthrosis at osteotomy site	0 (0%)	0 (0%)	1 (1.8%)	0.968
Iliac screw loosening	3 (25.0%)	2 (8.0%)	3 (15.0%)	0.671
Iliac screw breakage	0 (0%)	0 (0%)	0 (0%)	–
Any instrumentation failure	4 (33.3%)	17 (68.0%)	11 (55.0%)	0.262
Any postoperative complication	9 (75.0%)	18 (72.0%)	12 (60.0%)	0.825

Values expressed as number (percentage). Multiple comparison a: L5 PSO versus L4 PSO, b: L5 PSO versus L1-3 PSO, c: L4PSO versus L1-3 PSO. *Statistically significant difference

deformities and global spinopelvic malalignment than those with L1-3 kyphosis deformities (Table 2), L5 PSO provided adequate correction of the L4–S1 lordosis and HRQOL improvements, which were maintained throughout the 5-year follow-up period (> 5-year follow-up rates: 68%; Table 4 and Fig. 4). Thus, L5 PSO was relatively safe and reliable for extensive correction surgery, although patients with L5 PSO had greater EBL (2450 mL).

The relationship between PI and LL is commonly used to restore proper LL [14]. L4–S1 lordosis is two-thirds of the L1–S1 lordosis [15]. PSOs can provide sufficient correction in patients with rigid kyphosis deformities [2, 3] and are generally performed at the L3 or L4 level to correct the reduction in LL because this is less challenging than a L5 PSO [4]. Lateral dissection of the L5 vertebral body is challenging because of a significant vascular environment; thus, careful lateral dissection is required to prevent main vascular injuries [2]. L5 PSO offers the possibility of greater correction but carries a higher bleeding risk due to vascular injury [2]. Performing PSO at the kyphotic level was appropriate for obtaining anatomical correction with a physiologic LL shape [15, 16], which was the surgical policy used in our institution. In this study, a harmonious LL shape was obtained with PSO correction surgery at the

kyphosis level, demonstrating the usefulness of this surgical policy and technique. Spine surgeons should decide on the appropriate osteotomy level according to the kyphosis apex to restore proper LL and L4–S1 LL.

Alzakri et al. reported that correction surgery with L5 PSO for ASD patients was effective in obtaining good clinical outcomes until the 2-year follow-up [2]. Previous studies have shown that the mean EBL and length of surgery with correction surgery with L5 PSO were 2065–2985 mL and 354–465 min, respectively [1, 2]. Conversely, the mean EBL and length of surgery with L2-4 PSO were 1070–1515 mL and 241–275 min, respectively [4, 17]. Yoshida et al. reported that length of surgery ≥ 360 min and EBL ≥ 2000 mL were risk factors for in-hospital perioperative complications [18]. In this study, extensive correction surgery with L5 PSO was associated with serious issues, including longer length of surgery (473 min) and greater EBL (2450 mL), although there was no significant difference between L5 PSO, L4 PSO, and L1-3 PSO groups. L5 PSO tends to have greater EBL, which may be a risk of developing perioperative complications [18]. In particular, when performing L5 PSO, surgeons should try to reduce intraoperative bleeding for avoiding further perioperative complication.

Table 4 Scoliosis research society-22r, and Oswestry Disability Index scores in the L5 pedicle subtraction osteotomy (PSO), L4 PSO, and L1-3 PSO groups

	L5 PSO group (n = 12)	L4 PSO group (n = 25)	L1-3 PSO group (n = 20)	P value (ANOVA)	P value (Tukey)
<i>Preoperative score in SRS-22r domain</i>					
Function	2.2 ± 0.7	2.5 ± 0.7	2.8 ± 0.8	0.085	—
Pain	2.6 ± 1.0	2.9 ± 0.8	3.2 ± 0.8	0.132	—
Self-image	1.7 ± 0.7	2.2 ± 0.7	1.9 ± 0.6	0.085	—
Mental health	2.5 ± 0.5	2.6 ± 0.6	2.8 ± 0.7	0.465	—
Total	2.3 ± 0.6	2.6 ± 0.5	2.7 ± 0.5	0.083	—
<i>Score at 1 years postoperatively in SRS-22r domain</i>					
Function	2.9 ± 0.7	3.1 ± 0.7	2.9 ± 0.8	0.673	—
Pain	3.8 ± 0.5	3.7 ± 0.7	3.7 ± 0.9	0.859	—
Self-image	3.3 ± 0.9	3.6 ± 0.9	3.6 ± 0.8	0.626	—
Mental health	3.3 ± 0.3	3.3 ± 0.4	3.1 ± 0.7	0.438	—
Satisfaction	3.6 ± 0.9	3.4 ± 1.0	3.4 ± 0.8	0.752	—
Total	3.4 ± 0.5	3.4 ± 0.5	3.3 ± 0.6	0.863	—
<i>Score at 2 years postoperatively in SRS-22r domain</i>					
Function	3.1 ± 0.8	3.1 ± 0.6	3.2 ± 0.7	0.970	—
Pain	3.7 ± 0.6	3.6 ± 0.7	3.7 ± 0.9	0.778	—
Self-image	3.2 ± 0.8	3.4 ± 0.9	3.6 ± 0.9	0.578	—
Mental health	3.3 ± 0.4	3.2 ± 0.5	3.1 ± 0.6	0.542	—
Satisfaction	3.5 ± 0.9	3.5 ± 1.1	3.4 ± 0.8	0.945	—
Total	3.4 ± 0.5	3.3 ± 0.6	3.4 ± 0.6	0.951	—
<i>Score at 5 years postoperatively in SRS-22r domain**</i>					
Function	3.0 ± 1.1	3.1 ± 1.0	3.1 ± 1.3	0.985	—
Pain	3.9 ± 0.8	3.4 ± 0.9	3.2 ± 1.4	0.366	—
Self-image	3.5 ± 1.0	3.3 ± 0.9	3.0 ± 1.3	0.548	—
Mental health	3.3 ± 0.5	3.2 ± 0.5	2.9 ± 1.3	0.729	—
Satisfaction	3.6 ± 1.1	3.4 ± 1.0	3.3 ± 1.4	0.821	—
Total	3.4 ± 0.7	3.3 ± 0.7	3.1 ± 1.2	0.659	—
<i>Oswestry Disability Index</i>					
Preoperative score	56.3 ± 16.0	47.3 ± 16.0	38.9 ± 17.4	0.019*	*, b
Score at 1 year postoperatively	33.2 ± 14.2	34.5 ± 15.5	32.8 ± 20.8	0.944	—
Score at 2 year postoperatively	32.3 ± 16.1	36.4 ± 20.0	26.0 ± 17.2	0.177	—
Score at 5 year postoperatively**	33.6 ± 26.2	33.8 ± 18.0	24.2 ± 23.4	0.439	—

Values expressed as mean ± SD. Multiple comparison a: L5 PSO versus L4 PSO, b: L5 PSO versus L1-3 PSO, c: L4PSO versus L1-3 PSO.

*Statistically significant difference. Eight cases with L5 PSO, 18 cases with L4 PSO, and 13 cases with L1-3 PSO who were followed more than 5 years

SRS-22r, scoliosis research society-22r

In this study, transient motor deficits occurred without permanent deficits. Each foramen and nerve root were directly checked intraoperatively with the combination of multi-modal neuromonitoring. Extensive correction surgery was associated with a higher incidence of rod fractures than local correction fusion surgery [19]. The combination of satellite rod techniques for extensive correction surgery with three-column osteotomies can reduce the short-term incidence of rod fractures [20]. However, Alzakri et al. reported that the incidence of rod fractures requiring revision surgery was 30% (average follow-up

period, 4.0 years) after L5 PSO [2]. In our study, the incidence of rod fractures was high (40.4%) in PSO patients throughout the mid-term follow-up, consistent with the previous report. Conversely, previous studies have shown that the rate of PJFs requiring revision surgery was 13.0–14.2% post-extensive correction surgery, including spinopelvic fixation in ASD [21, 22]. Furthermore, aging, previous spinal surgery, TK, and UIV level at the thoracolumbar junction were also associated with PJF [23, 24]. Funao et al. reported that the rate of PJFs requiring revision surgery was 28% (7/25) after L5 or sacrum PSO

[1]. Alzakri et al. reported no PJFs after L5 PSO [2] and hypothesised that restoration of the anatomical L4–S1 lordosis following L5 PSO was associated with PJF prevention. In this study, the rate of PJFs requiring revision surgery was 8.8% (5/52) after L1-5 PSO, supporting the hypothesis of Alzakri et al. L5 PSO increases the risk of iliac screw loosening or pseudoarthrosis at the osteotomy site due to the too few bony anchors; thus, we used bilateral dual iliac screws to secure enough bony anchors. L5 PSOs using bilateral dual iliac screws had similar rates of pseudoarthrosis at the osteotomy site and iliac screw loosening as L4 and L1-3 PSOs.

L5 PSO achieves good radiological and clinical outcomes in patients with rigid kyphosis deformities of multiple aetiologies [1, 2, 4]. After performing L5 PSOs in 10 patients with a distal junctional kyphosis or iatrogenic flat back (mean age 50.3 years), Alzakri et al. reported improved visual analogue pain scores, from 7.56 preoperatively to 3.61 postoperatively [2]. In a similar study on 25 patients who underwent L5 or sacrum PSOs for rigid kyphosis deformity correction (median age, 56.0 years), Funao et al. reported improvements in ODIs from 63.0 to 40.0, with significant improvements in SRS-22r [1]. This study also demonstrated an improvement in the ODI from 56.3 to 33.6 in patients who underwent L5 PSO despite the mean age of 67.5 years, and all domains of the SRS-22r improved, with improvements maintained throughout the 5-year postoperative period. Our study is the first report to reveal that L5 PSO yields good mid-term radiological and clinical outcomes in elderly patients with rigid kyphosis deformities.

This study had several limitations. First, it was a small, retrospective study with a postoperative observation period of > 2 years. This may limit the generalisability of the results. Second, it included only patients with rigid kyphosis deformities. Third, there were some issues in defining sagittal imbalance. Le Huec et al. reported that the odontoid hip axis angle was the most efficient parameter for evaluating global balance, including the consideration of compensatory mechanisms [25]. However, sagittal global alignment was evaluated using C7 SVA on standing whole spine radiographs because in some cases, the whole spine radiographs did not include the odontoid. We will actively incorporate this parameter when evaluating global alignment in future studies. Finally, the PSO level was selected based on the vertebral body at the kyphosis deformity apex; thus, osteotomy levels were not compared among patients with similar spinal shapes and alignment. It was difficult to directly compare clinical outcomes between L5, L4, and L1-3 PSOs. We hope to follow this study with a well-designed multicentre randomised controlled trial with a large sample size to confirm the impact of L5 PSO for rigid kyphosis deformity correction on clinical outcomes. Although selection bias may exist, this study found that L5 PSO had similar

postoperative complication rates as L4 and L1-3 PSO in terms of improvements and maintenance of sagittal malalignment and HRQOL.

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Author contributions YM supervised the study. TH was responsible for the study's conception and design. HU acquired, analysed, and interpreted the data; drafted the article; and approved the final version on behalf of all authors. All authors have critically revised the article and reviewed the submitted version.

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Availability of data and material The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Compliance with ethical standards

Conflict of interest Dr. Yamato and Dr. Oe work for a donation-funded laboratory called the “Division of Geriatric Musculoskeletal Health”. Donations to this laboratory were received from Medtronic Sofamor Danek, Inc., Japan Medical Dynamic Marketing, Inc., and Meitoku Medical Institution Jyuzen Memorial Hospital. The other authors declare no conflicts of interest.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication Patients signed informed consent regarding publishing their data and photographs.

Ethical approval The study protocol was approved by the Institutional Review Board of Hamamatsu University School of Medicine (No. 14-306). The study was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

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