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Clinical Study

Comparison of clinical and radiological outcomes of three-column lumbar osteotomies with and without interbody cages for adult spinal deformity

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Abbreviations and Acronyms: 3CO, Three-column osteotomy; ANOVA, Analysis of variance; ASD, Adult spinal deformity; BMP-2, Bone morphogenetic protein 2; CI, Confidence interval; ml, Milliliters; n, Number; OR, Odds ratio; PJK, Proximal junctional kyphosis; PROMs, Patient reported outcome measures; PSO, Pedicle subtraction osteotomy; SRS22r, Scoliosis Research Society-22 revised; SVA, Sagittal vertical axis

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Abstract

BACKGROUND CONTEXT: Correcting sagittal malalignment in adult spinal deformity (ASD) is a challenging task, often requiring complex surgical interventions like pedicle subtraction osteotomies (PSOs). Different types of three-column osteotomies (3COs), including Schwab 3, Schwab 4, Schwab 4 with interbody cages, and the "sandwich" technique, aim to optimize alignment and fusion outcomes. The role of interbody cages in enhancing fusion and segmental correction remains unclear.

PURPOSE: This study aimed to compare outcomes among these 4 3CO techniques, evaluating the impact of cage use at the osteotomy site on postoperative radiographic imaging and clinical outcomes.

STUDY DESIGN/SETTING: This is a multicenter retrospective study utilizing data from a prospective multicenter database of patients undergoing complex ASD surgery.

PATIENT SAMPLE: Ninety-seven patients who underwent 1 of 4 3CO techniques for thoracolumbar ASD correction with at least 2 years of follow-up were included. The sample consisted of 29 patients who underwent Schwab 3 osteotomy, 20 Schwab 4, 28 Schwab 4 with interbody cages, and 20 who underwent "sandwich" osteotomy.

OUTCOME MEASURES: The Scoliosis Research Society-22 revised (SRS22r) questionnaire evaluating pain, activity, appearance, mental health, and satisfaction was used to evaluate patient reported outcomes and radiographic measures including segmental lordosis and fusion rates determined by 3 blinded reviewers were used to evaluate physiologic outcomes.

METHODS: This study analyzed demographic data, radiographic outcomes, patient-reported outcomes, complications, and fusion rates over a 2-year follow-up period. Fusion status was determined via serial radiographs and evaluated independently by 3 blinded reviewers. Univariate and multivariate statistical analyses were performed to assess differences among the groups and the impact of interbody cage use on outcomes.

RESULTS: Patients undergoing "sandwich" osteotomy exhibited worse preoperative leg pain scores and lower SRS22r activity (p=.015), appearance (p=.007), and mental health domain scores (p=.0015). No differences in complications were found among groups (p>.05). Patients who underwent osteotomy with a cage were more likely to have had previous spine fusion (91.7% vs. 71.4%, p=.010). Additionally, these patients had lower preoperative SRS22r mental domain (2.9±1 vs. 3.5±1, p=.009), satisfaction (2.3±1 vs. 2.7±1.2, p=.034), and SRS22r total scores (2.3±0.6 vs. 2.6±0.6, p=.0026) but demonstrated the greatest improvement in the mental health domain (0.9±0.7 vs. 0.3±0.9, p=.002). Cage use was associated with a larger mean change in segmental lordosis at the osteotomy site (32.9±9.6 vs. 28.7±9.5, p=.038). Fusion rates were significantly higher in the cage group (79.2% vs. 55.1%, p=.0012). Regression analysis identified cage use as an independent predictor for fusion (odds ratio, 3.338; 95% confidence interval, 1.108-10.054, p=.032).

CONCLUSIONS: Interbody cage use at the osteotomy site during 3COs for ASD correction was associated with improved fusion rates and greater segmental lordosis without increasing complication rates. Incorporating cages may provide enhanced alignment and fusion outcomes in complex ASD surgeries.

Keywords: Fusion; Patient-reported outcomes; Pedicle subtraction osteotomies; Schwab osteotomy; Surgical complications; Three-column osteotomy

Introduction

With a nearly 200% surge in the performance of fusions for degenerative lumbar pathologies over the last 2 decades [1], the number of patients experiencing iatrogenic flat back syndrome and fixed deformity is expected to rise [2]. It is estimated that addressing spinopelvic complications after lumbar and thoracolumbar surgery could cost as much as $1 billion over 5 years, with an estimated annual reoperation rate of 27,580 cases in the USA [3]. Despite the benefits of modern implants, improper utilization of instrumentation and poor technique during fusion for lumbar degenerative conditions can result in spinopelvic misalignment and fixed imbalance postoperatively [2].

Fixed spinal malalignment is one of the key hallmarks of adult spinal deformity (ASD), and has a prevalence as high as 68% [4]. Fixed sagittal imbalance can arise not only iatrogenically but also in association with ankylosing spondylitis, thoracolumbar fractures, or severe lumbar degeneration [5].

Patients with sagittal malalignment activate compensatory mechanisms to maintain the center of gravity within the cone of economy [6]. However, these mechanisms often fail rapidly in cases of significant spinal deformity, leading to muscular fatigue, walking disability, and the inability to maintain an upright posture [7]. These factors collectively contribute to a poor quality of life, sometimes even surpassing that of patients with severe diabetes, heart failure, cancer, or renal disease [8].

When spine surgeons encounter patients with severe ASD accompanied by fixed sagittal malalignment, high-grade lumbar osteotomies emerge as crucial tools in their arsenal [9]. The comprehensive anatomical spinal osteotomy classification, published by Schwab et al. in 2014 [10], categorizes spinal osteotomies from grades 1 to 6 based on the extent of bone resection in the thoracolumbar spine [10]. Among these, grades 3 and 4 osteotomies encompass a spectrum ranging from the traditional pedicle subtraction osteotomy (PSO) (Schwab grade 3) to more complex techniques involving disc resection and use of interbody cages, including the Schwab 4, Schwab 4 with a cage, and the "sandwich" osteotomy, all of which play significant roles in fixed sagittal plane correction in spine deformity surgery [10].

A PSO involves partial resection of the vertebral body and all posterior elements, including the pedicles, allowing for correction of the deformity ranging from 25° to 35° [11,12]. When the PSO extends into the disc space, it becomes a Schwab 4 osteotomy [10], entailing a wider wedge resection of the posterior vertebral elements. Various modifications of these techniques have been described [10,13,14], including the recently introduced "sandwich" osteotomy, incorporating anterior support with interbody spacers above and below the PSO [15]. Despite numerous case series [12,16–18] reporting outcomes of PSO and modified PSO techniques, only one single-center study has compared outcomes of Schwab 4 osteotomy with and without interbody fusion in 31 and 24 patients, respectively [16]. Those authors conducted a limited univariate analysis focusing on postoperative change in segmental lordosis and mechanical failure [16]. No other research has directly compared Schwab 3 (Fig. 1A), Schwab 4 (Fig. 1B), Schwab 4 with an interbody cage (Fig. 1C), and the "sandwich" osteotomy (Fig. 1D). Additionally, despite multiple studies assessing the rate of pseudarthrosis after three-column osteotomies (3COs) [16,18–20], with rates ranging from 0% to 56% [18], few studies [21] have evaluated the rate of fusion at the osteotomy site after these procedures. This is notable due to the high degree of segmental instability after PSO or extended PSO [22]. X-rays are the most commonly used method to assess fusion and are utilized in approximately 60% of studies [23,24]. The sensitivity and specificity for X-rays in determining fusion in interbody fusion cases are 90% and 89%, respectively, comparable to those reported for CT [24].

The primary objective of this study was to compare patient-reported outcomes (PROMs) and radiographic outcomes, including fusion rates, after a 2-year follow-up among patients who underwent various types of 3COs. An additional aim was to investigate whether incorporating a cage at the osteotomy site contributed to enhanced fusion rates.

Methods

This is a retrospective analysis of a prospective multicenter ASD database. The database includes consecutive patients with ASD enrolled in the Prospective, Multi-Center Adult Spinal Deformity Outcomes Database Registry (PON; clinical trial identifier NCT00738439 https://clinicaltrials.gov/study/NCT00738439). Database enrollment was performed at 14 institutional review board-approved sites across the United States. The included patients comprised those in the database from its 2008 inception through 2021, to obtain a follow-up of at least 2 years postoperatively.

At the time of hospital admission for the spinal surgery, informed consent for patient procedures to be performed and data to be published was provided by each patient or a

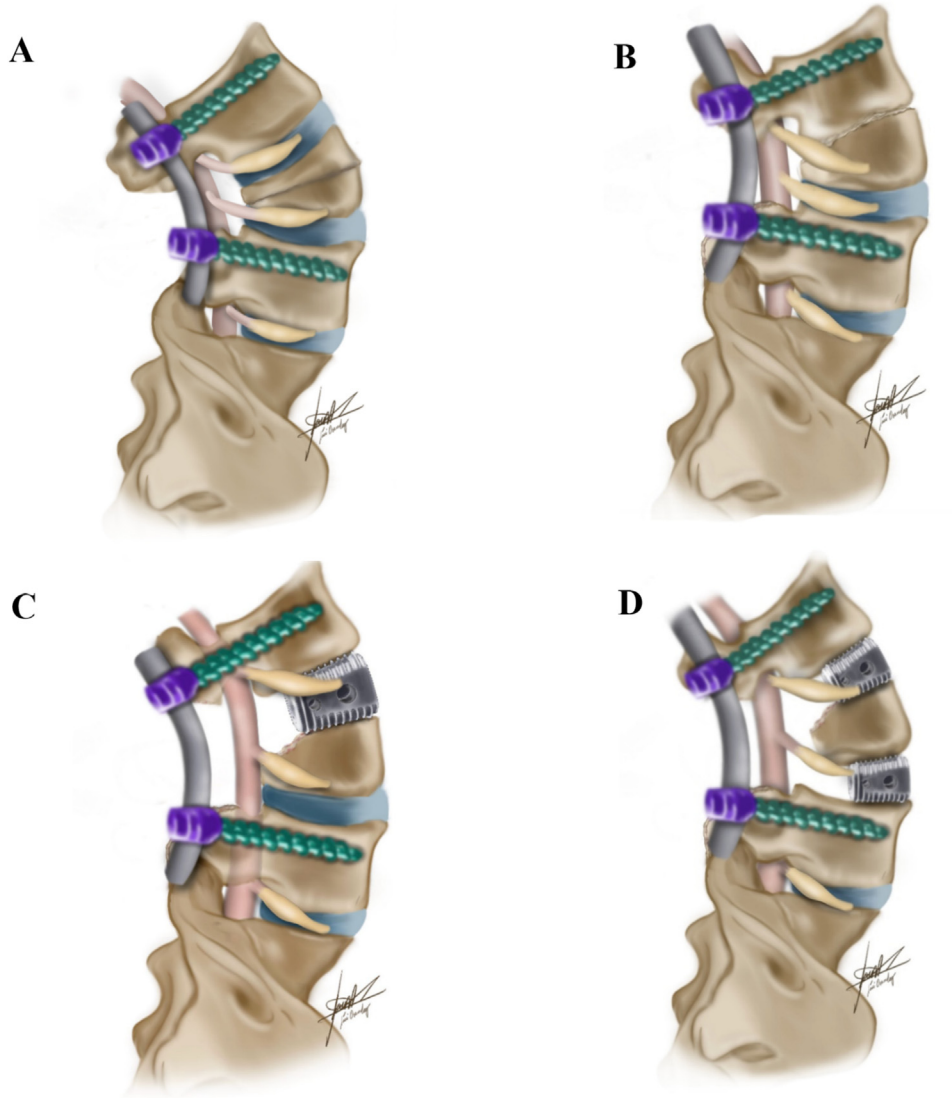

Fig. 1. Illustrations of (A) classic Schwab 3 osteotomy, (B) Schwab 4 osteotomy without cage, (C) Schwab 4 osteotomy with cage, and (D) sandwich osteotomy.

legally authorized representative. We followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines [25]. Data supporting the study findings are available from the corresponding author on reasonable request.

Patient selection

This study was comprised of adults ≥18 years of age who underwent complex spinal deformity surgery for thoracolumbar ASD, as defined by one or more of the following criteria: 1) diagnosis of adult degenerative deformity with a coronal curvature of the spine measuring ≥20°, 2) sagittal vertical axis (SVA) >5 cm, pelvic tilt (PT) >25°, and thoracic kyphosis >60°. Patients were eligible if they had preoperative and postoperative PROMs and radiographic follow-up of at least 2 years and had undergone a Schwab 3 [10], Schwab 4 [10], Schwab 4 with a cage, or "sandwich" extended PSO [15] (Fig. 2A-D). Patients were excluded if they had a diagnosis of scoliosis other than degenerative or idiopathic (i.e., neuromuscular or congenital). Different types of osteotomies were selected based on operating surgeons' goals of obtaining postoperative improvement in alignment parameters that were tailored to patients on an individual basis. Overall, the goals of surgery were to reduce the sagittal vertical axis and pelvic tilt according to each patient's specific characteristics, including age and spinopelvic alignment (Fig. 3).

Data extraction and definition of variables

The demographic data collected included the patient's age, sex, body mass index, Charlson Comorbidity Index, American Society of Anesthesiologists' physical status

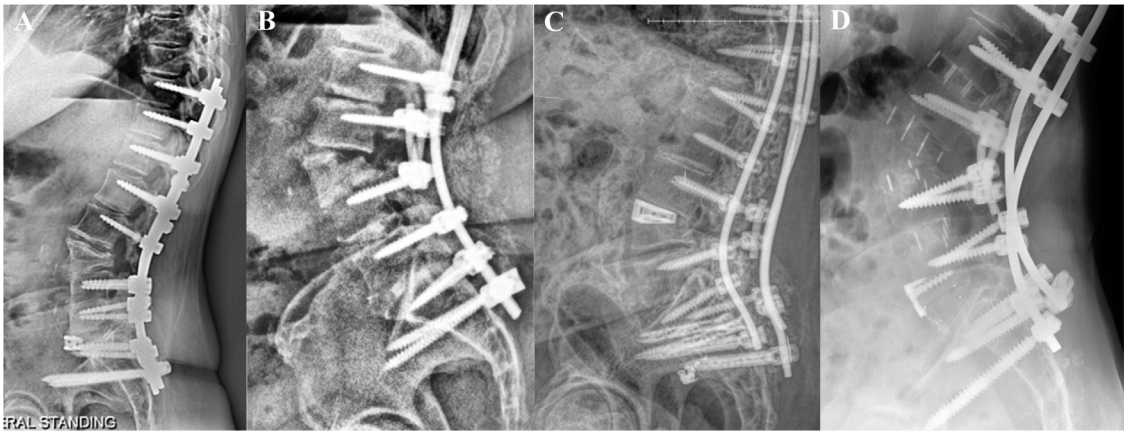

Fig. 2. Lumbar x rays demonstrating (A) classic Schwab 3 osteotomy, (B) Schwab 4 osteotomy without cage, (C) Schwab 4 osteotomy with cage, and (D) sandwich osteotomy.

grade, smoking status, and history of spine surgery and/or fusion. Preoperative and postoperative neurologic examination findings in the lower limbs were assessed using the American Spinal Injury Association lower extremity motor score, which was developed to evaluate motor function on a scale of 0 (no motor function) to 5 (full motor function) for 5 lower extremity muscle groups with a 50-point maximum (25 points per side) [26]. Preoperative radiographic measurements comprised preoperative sacral slope, pelvic tilt, pelvic incidence, lumbar mismatch, lumbar lordosis, and sagittal vertical axis. The preoperative and mean changes in segmental lordosis were compared between groups; these changes were measured with the sagittal Cobb angle from the superior endplate of the vertebra above and inferior endplate of the vertebra below the osteotomy [16]. Preoperative patient-reported outcomes encompassed the Oswestry Disability Index and the Scoliosis Research Society-22 revised (SRS22r) outcome measure, which included the domains of activity, pain, mental health, appearance, satisfaction, and the total SRS22r score. Back pain and leg pain were recorded according to the visual analog pain scale from 0-10. All radiographic and PROMs were reported as mean changes at the 2-year follow-up.

The surgical variables analyzed included procedure duration from skin incision to wound closure, estimated blood loss, number of allotransfused blood units, number of transfused frozen plasma units, amount of colloids and crystalloids required during the osteotomy in milliliters (ml), number of instrumented levels, and use of a satellite or an accessory rod, an anterior approach, or bone morphogenetic protein 2 (BMP-2). Postoperative variables included the same preoperative radiographic measurements, but obtained at 2 years postoperatively, and the presence of overall complications, reoperation, postoperative motor deficit, proximal junctional kyphosis (PJK), intraoperative Dural tear, new postoperative radiculopathy, rod breakage, presence of radiolucency, cardiopulmonary complications (including arrhythmia, infarction, decompensated heart failure), and pulmonary edema. Wound infection rates were also recorded and analyzed. Fusion rates were defined according to Lenke classification [27] as follows: a. definitely solid with bilateral stout fusion masses present; b.

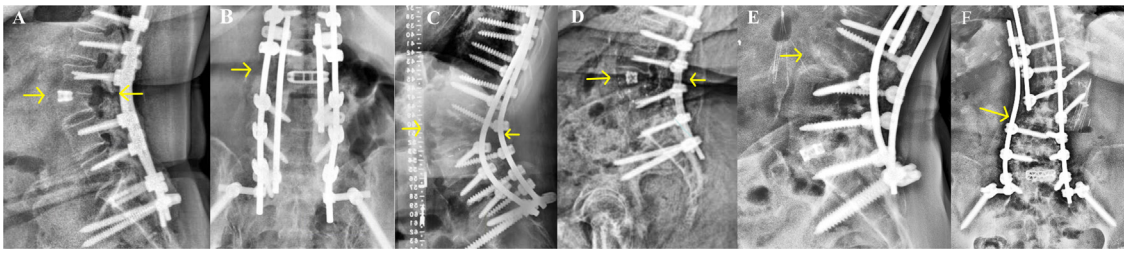

Fig. 3. Anteroposterior (AP) and lateral lumbar X-rays demonstrating cases of nonfusion at the 2-year mark: (A) Lateral lumbar X-ray showing the absence of solid fusion at the osteotomy site without bridging bone across the anterior border of the cage (left arrow) and persistent radiolucency across the posterior osteotomy defect on the lateral image (right arrow). (B) AP lumbar X-ray showing no clear bilateral posterolateral fusion mass at the osteotomy site, as indicated by the yellow arrow. (C) Lateral lumbar X-ray demonstrating persistent radiolucency across the osteotomy site without evidence of a fusion mass anteriorly and posteriorly, indicated by the yellow arrows. (D) Lateral lumbar X-ray showing a complete collapse of the vertebra below the osteotomy, with minimal posterior fusion mass at the fusion level and rod breakage at the osteotomy, as indicated by the yellow arrows and radiolucency on the screws at L5. (E and F) Lateral and AP lumbar X-rays demonstrating the absence of fusion mass across the osteotomy site both anteriorly (arrow on E) and posteriorly, with a persistent radiolucent line on the AP projection at the osteotomy site 2 years postoperatively, highlighted by the yellow arrow on F.

probably solid with a unilateral stout fusion mass and contralateral thin fusion mass; c. probably not solid with a thin unilateral fusion mass and probably pseudoarthrosis on the contralateral side; or d. definitely not solid with thin fusion masses bilaterally with obvious pseudoarthrosis or bone graft dissolution bilaterally. Categories a. and b. were considered fusion and categories c. and d. were considered nonfusion [27,28]. Fusion grading and radiographic parameters were determined independently by 3 blinded reviewers—none of whom had operated on the included patients—based on serial scoliosis x-rays. Any discrepancies among the reviewers' determinations were resolved by consensus.

Statistical analysis

Data were presented as the mean ± standard deviation (SD) for continuous variables and as frequencies with percentages for categorical variables. Statistical analyses were conducted using SPSS, version 29.0 (IBM Corp., Armonk, NY). An analysis of variance (ANOVA) was performed, categorizing patients into 4 groups: Schwab 3, Schwab 4, Schwab 4+cage, and "sandwich" osteotomy. Additionally, patients who underwent Schwab 4+cage and the "sandwich" technique were amalgamated into the cage group, and traditional Schwab 3 and Schwab 4 formed the group without cages. Moreover, univariate analyses were conducted between the with and without cage groups, employing independent sample t-tests, Chi-square, and Fisher's exact test. We used linear regression models to predict the mean change in segmental lordosis reporting β coefficients, and multivariate logistic regression models to analyze predictive variables for fusion at the osteotomy site, presenting odds ratios (OR) with corresponding 95% confidence intervals (CI). All tests were 2-tailed, and p-values <.05 were considered statistically significant.

Results

Distribution of patients

Ninety-seven patients from the database fulfilled the inclusion criteria, undergoing Schwab 3, Schwab 4, Schwab 4 with a cage, or "sandwich" osteotomies, with available follow-up at 2 years postoperatively. Fifty-six of the 97 patients (57.7%) underwent the osteotomy at L3, and 25 (25.8%) underwent the osteotomy at L4. Additionally, 14 patients (14.4%) underwent the osteotomy at L2, 1 patient (1%) underwent the osteotomy at L5, and 1 patient (1%) underwent the osteotomy at L1.

Comparison of Schwab 3, Schwab 4, Schwab 4+Cage, and "sandwich" osteotomies

Demographic and preoperative PROMs

When categorized into 4 groups—Schwab 3 osteotomy (n=29,29.9%), Schwab 4 osteotomy (n=20,20.6%), Schwab 4+cage (n=28,28.9%), and "sandwich" osteotomy (n=20,20.6%) (Table 1)—no significant differences were observed among groups regarding age, sex, body mass index, smoking status, preoperative motor score, back pain or previous spine surgery or fusion. However, the ANOVA test (Table 1) revealed that preoperative SRS22r appearance scores were lower in the Schwab 4+cage group (2±0.7) and in the "sandwich" osteotomy group (1.9±0.5) (p=.007). The "sandwich" osteotomy group had higher preoperative leg pain scores (7.10±2.6, p=.04), lower SRS22r activity domain scores (2.02±0.5, p=.015), lower SRS22r mental health scores (2.8±0.9, p=.015), and lower SRS22r total scores (2.1±0.5, p=.004) than the other groups.

Surgery-related variables, complications, and radiographic parameters

No statistically significant differences were found in most surgical variables, including the number of patients undergoing an anterior approach and the utilization of BMP-2 (Table 2). The only significant difference observed was in the use of satellite rods (p<.001) (Table 2), with a notably higher percentage utilized in the "sandwich" osteotomy group (65%) and a low percentage (3.6%) in the Schwab 4+cage group. No significant differences in complications were observed among groups including overall complications, reoperation, postoperative motor deficit, PJK, Dural tear, new postoperative radiculopathy, rod breakage, radiolucency, cardiopulmonary complications, and wound infections (all p>.05) (Table 2). Preoperative radiographic parameters in the lumbar spine did not significantly differ between groups except for preoperative segmental lordosis, which was lower in the Schwab 4+cage group (0.7±12.2) and higher in the "sandwich" osteotomy group (11.2±15.5) p=.044. However, there were no significant postoperative differences in the mean change in radiographic variables, including segmental lordosis, at 2 years (Table 1).

Fusion and PROMs at 2 years of postoperative follow-up

Although the p-value for fusion was .018, post hoc analysis revealed that it did not meet the significance threshold after Bonferroni correction, rendering the results nonsignificant. In terms of PROMs at 2 years, the only difference between groups was a significantly larger improvement in the SRS mental domain in the "sandwich" osteotomy group (p=.005).

Comparison between the osteotomy with and without cages groups

When categorized into these 2 groups, a total of 49 (50.5%) patients underwent osteotomies without cages, and 48 (49.5%) underwent osteotomies with cages (Table 3).

Demographic and preoperative PROMs

Patients who underwent osteotomies with cages were more likely to have had previous spine fusion (91.7% vs.

Table 1
Preoperative, perioperative, and postoperative continuous variables in 97 patients across 4 osteotomy groups*

Variables	Total 3COs (n=97)	Schwab 3 (n=29)	Schwab 4 (n=20)	Schwab 4+cage (n=28)	Sandwich technique (n=20)	p-value†,‡
Age (years)	65.1±8.3	66.9±9.3	66.4±6.9	63.7±7.4	63.2±8.9	.219
BMI	30.08±6.25	31.01±6.2	30.1±4.8	29.9±7.1	28.8±6.4	.702
Preoperative LEMS	48.7±3.5	49.03±1.9	47.55±6.3	49.04±2.34	48.7±2.9	.462
LEMS at 6-week follow-up	48.6±3.6	48.45±2.9	47.5±6.3	48.93±2.6	49.3±1.26	.416
LEMS at 2-year follow-up	49.2±2.3	49.3±1.5	48.5±3.2	49.0±2.86	49.9±0.3	.260
Preoperative back pain	7.54±2.2	7.38±2.2	7.95±1.90	7.43±2.3	7.50±2.7	.836
Back pain at 6-week follow-up	5.07±2.7	4.34±2.7	6.05±3.1	4.86±2.3	5.47±2.8	.161
Back pain at 2-year follow-up	3.97±3	3.76±3.05	3.6±3.5	4.2±2.8	4.3±3.01	.841
Back pain mean difference at 2-year follow-up	−3.6±2.9	−3.6±2.7	−4.3±3.2	−3.2±2.9	−3.2±2.8	.548
Preoperative leg pain	5.54±3.1	5.72±2.7	4.95±3.6	4.64±3.2	7.10±2.6	**.040**
Leg pain at 6-week follow-up	3.67±3.1	3.31±3.3	4.40±3.4	3.0±2.9	4.42±2.45	.273
Leg pain at 2-year follow-up	3.85±3.3	3.62±3.5	4.5±3.6	3.07±2.9	4.6±2.9	.319
Leg pain mean difference at 2-year follow-up	−1.7±3.5	−2.1±4.0	−0.45±3.5	−1.5±2.9	−2.5±3.5	.261
ODI	51.2±15.8	47.9±16.4	54.5±14.9	48.03±14.9	57.03±15.4	.109
SRS22r activity	2.5±0.8	2.6±0.9	2.3±0.6	2.6±0.8	2.02±0.5	**.015**
SRS22r pain	2.1±0.8	2.2±0.8	2.1±0.6	2.1±0.8	1.8±0.6	.216
SRS22r appearance	2.1±0.7	2.5±0.9	1.9±0.6	2±0.7	1.9±0.5	**.007**
SRS22r mental health	3.2±1.0	3.7±1.0	3.1±0.9	3.0±1.0	2.8±0.9	**.015**
SRS22r satisfaction	2.5±1.1	2.9±1.1	2.5±1.2	2.5±1.0	1.9±0.9	.25
SRS22r total score	2.5±0.7	2.8±0.7	2.4±0.5	2.4±0.7	2.1±0.5	**.004**
PROMs mean change at 2-year follow-up						
ODI	−14.7±18.4	−12.4±18.0	−14.5±23.9	−13.9±17.4	−19.3±13.5	.630
SRS22r activity	0.8±0.9	0.6±0.9	0.7±0.8	0.9±1.0	1.1±0.8	.336
SRS22r pain	0.9±2.4	1.2±0.9	1.2±1.2	−0.08±4.0	1.3±0.8	.112
SRS22r appearance	1.1±1.1	0.8±1.2	1.3±1.2	1.2±0.9	1.2±0.9	.345
SRS22r mental health	0.8±0.7	0.15±1.0	0.6±0.8	0.9±0.8	1.0±0.6	**.005**
SRS22r satisfaction	1.7±1.3	1.6±1.2	1.4±1.2	1.7±1.3	1.8±1.5	.800
SRS22r total score	1±0.7	0.8±0.7	1.0±0.7	1.0±0.8	1.2±0.6	.230
Surgery-related variables						
Allotransfused blood units	3.6±4.2	3.2±2.9	3.1±3.8	4.6±6.1	2.9±2.5	.465
Transfused frozen plasma units	1.9±4.7	1.0±2.5	1.25±2.5	3.6±7.7	1.35±2.3	.138
EBL (ml)	2766±2077	2604±1573	2895±2574	3122±2588	2372±1265	.623
Operative duration (minutes)	464.4±168.3	477.0±176.2	459.0±147	453.0±182.0	468.0±167.0	.957
Colloids (ml)	767.4±873.1	940.9±910.6	525.0±701.9	805.36±849.6	705.0±998.5	.422
Crystalloid (ml)	3923.9±2258.9	4102.6±2046.7	4622.7±3284.9	3489.3±1767.4	3574.7± 1846.3	.310
Extent of instrumentation (n of levels)	10.9±3.4	10.6±3.3	11.9±3.6	10.5±3.2	10.6±3.6	.455
LOS (days)	9±4.5	8.5±3.9	9.35±6.5	8.9±3.8	9.35±4.1	.897
Preoperative radiographic parameters						
SS°	24.8±10.6	24.3±11.3	25.0±11.5	23.4±9.5	27.3±10.5	.662
PT°	31.6±9.1	31.3±8.9	30.5±9.2	33.4±11.1	30.8±6.0	.672
PI°	56.4±10.9	55.6±10.2	55.4±11.5	56.8±11.9	58.1±10.1	.839
PI-LL° (mismatch)	35.8±14.4	34.3±11.7	35.4±12.4	39.5±17.1	33.2±15.6	.425
Segmental lordosis°	6.25±13.8	6.1±14.48	9.1±11.1	0.7±12.2	11.2±15.5	**.044**
L1-S1 lordosis°	20.7±16.1	21.3±15.4	20.0±13.2	17.4±15.6	24.9±19.9	.454
SVA (mm)	138.1±67.2	139.9±61.5	122.8±56.5	141.0±72.9	146.7±78.4	.700
Radiographic measurements mean change at 2-year follow-up						
SS°	8.2±8.1	6.4±8.1	10.5±10.3	6.9±6.9	10.2±6.8	.172
PT°	−7.8±7.6	−6.7±7.9	−10.6±9.8	−7.1±6.4	−7.7±5.9	.318
PI°	0.3±4.0	−0.31±1.8	−0.11±2.1	−0.15±2.1	2.4±7.6	.062
PI-LL° (mismatch)	−31±13.9	−30.6±13.4	−32.0±12.4	−32.4±16.8	−28.7±12.4	.820
Segmental lordosis°	30.8±9.7	28.1±10.7	29.7±7.6	32.7±8.5	32.9±11.1	.200
L1-S1°	31.4±14.2	30.3±13.6	31.9±12.6	32.24±16.37	31.2±14.4	.960
SVA (mm)	−86.4±67.0	−90.2±57.6	−68.7±81.9	−95.4±60.5	−86.0±73.5	.579

* All variables are presented as means ± standard deviations.
† Bold font indicates statistical significance.
‡ ANOVA among the 4 groups.Abbreviations: ANOVA, analysis of variance; BMI, body mass index; LEMS, Lower Extremity Motor Score; LL, lumbar lordosis; LOS, length of (hospital) stay; n, number; ODI, Oswestry disability index; PI, pelvic incidence; PT, pelvic tilt; SRS, Scoliosis Research Society; SS, sacral slope; SVA, sagittal vertical axis.

Table 2
Preoperative, surgical, and postoperative characteristics comparing dichotomous outcomes in patients among the osteotomy groups*

Variables	Schwab 3 (n=29)	Schwab 4 (n=20)	Schwab 4+cage (n=28)	"Sandwich" technique (n=20)	p-value†
Women	18 (62.1)	14 (70)	18 (64.3)	10 (50)	.613
Current smoker	1 (3.4)	1 (5)	1 (3.6)	1 (5)	.98‡
Vertebral level where the 3CO was performed					
L1	1 (3.4)	0 (0)	0 (0)	0 (0)	.594§
L2	4 (13.8)	1 (5)	8 (28.6)	1 (5)	
L3	17 (58.6)	14 (70)	14 (50)	11 (55)	
L4	7 (24.1)	5 (25)	5 (17.9)	8 (40)	
L5	0 (0)	0 (0)	1 (3.6)	0 (0)	
ASA score					
1	0 (0)	0 (0)	1 (3.6)	0 (0)	.092§
2	9 (31)	9 (45)	14 (50)	7 (35)	
3	20 (69)	11 (55)	12 (42.9)	13 (65)	
4	0 (0)	0 (0)	1 (3.6)	0 (0)	
CCI score					
0	6 (20.7)	3 (15)	8 (28.6)	4 (20)	.528§
1	6 (20.7)	3 (15)	7 (25)	5 (25)	
2	5 (17.2)	7 (35)	4 (14.3)	6 (30)	
3	3 (10.3)	5 (25)	3 (10.7)	1 (5)	
4	4 (13.8)	1 (5)	0 (0)	2 (10)	
5	2 (6.9)	0 (0)	3 (10.7)	2 (10)	
6	3 (10.3)	1 (5)	3 (10.7)	2 (10)	
Surgical variables					
Previous spine surgery	25 (86.2)	18 (90)	26 (92.9)	19 (95)	.727
Previous spine fusion	20 (69)	15 (75)	26 (92.9)	18 (90)	.075
Satellite rods	11 (37.9)	9 (45)	1 (3.6)	13 (65)	**<.001**
Accessory rods	9 (31)	7 (35)	17 (60.7)	4 (20)	.022‖
Anterior approach	2 (6.9)	1 (5)	3 (10.7)	4 (20)	.424‡
Use of BMP-2	25 (86.2)	13 (65)	18 (64.3)	13 (65)	.205
Postoperative surgical complications					
Overall complications	17 (58.6)	11 (55)	20 (71.4)	7 (35)	.095
Reoperation	6 (20.7)	7 (35)	10 (35.7)	5 (25)	.553
Postoperative motor deficit	1 (3.4)	2 (10)	0 (0)	0 (0)	.167‡
PJK	4 (13.8)	3 (15)	5 (17.9)	3 (15)	.97‡
Dural tear	4 (13.8)	1 (5)	4 (14.3)	1 (5)	.52‡
New postoperative radiculopathy	2 (6.9)	3 (15)	4 (14.3)	0 (0)	.302‡
Rod breakage	6 (20.7)	3 (15)	6 (21.4)	6 (30)	.715
Radiolucency	3 (10.3)	6 (30)	2 (7.1)	2 (10)	.152‡
Cardiopulmonary	3 (10.3)	0 (0)	3 (10.7)	2 (10)	.274‡
Wound infection	2 (6.9)	2 (10)	2 (7.1)	1 (5)	.940‡
2 years postoperative fusion					
Fusion	13 (44.8)	14 (70)	23 (82.1)	15 (75)	.018[a]

* Values are presented as numbers of patients and percentages; n (%).
† **Bold font** indicates statistical significance.
‡ Likelihood ratio chi-square test (for comparisons involving events with expected count <5 and >2 variables).
§ Linear by linear association (for ordinal variables).
‖ Post hoc test Bonferroni correction p-value considered significant if p<.006.Abbreviations: 3CO, 3 column osteotomy; ASA, American Society of Anesthesiologist; BMP-2, bone morphogenetic protein; CCI, Charlson Comorbidty Index; PJK, proximal junctional kyphosis.

71.4%, p=.010). Similarly to the findings in the 4-group comparison, patients who underwent osteotomies with cages were more likely to have lower preoperative SRS22r mental scores (2.9±1 in the cage group vs. 3.5±1 in the noncage group, p=.009), lower SRS22r satisfaction scores (2.3±1 in the cage group vs. 2.7±1.2 in the noncage group, p=.034), and lower overall SRS22r scores (2.3±0.6 in the cage group vs. 2.6±0.6 in the noncage group, p=.026) (Table 3).

Surgery-related variables, complications, and radiographic parameters

No differences were observed between the with and without cages groups in terms of perioperative variables and complications. When radiographic parameters were analyzed, the postoperative mean change in segmental lordosis was different between groups, with better improvement in the osteotomies with cages group (32.9±9.6 vs. 28.7±9.5, p=.038). No other significant

Table 3
Preoperative and postoperative continuous variables in the osteotomy groups with and without cages*

Variable	Without cages (n=49)	With cages (n=48)	p-value†
Age (years)	66.7±8.3	63.5±8.0	.055
BMI	30.4±5.8	29.7±6.7	.347
Preoperative LEMS	48.43±4.3	48.9±2.6	.517
LEMS at 6-week follow-up	48.06±4.6	49.1±2.1	.163
LEMS at 2-year follow-up	49.00±2.4	49.4±2.2	.424
Preoperative back pain	7.61±2.08	7.46±2.45	.740
Back pain at 6-week follow-up	5.04±2.9	4.11±2.5	.908
Back pain at 2-year follow-up	3.69±3.2	4.25±2.8	.370
Back pain mean difference at 2-year follow-up	−3.92±2.9	−3.21±2.9	.235
Preoperative leg pain	5.41±3.1	5.67±3.1	.685
Leg pain at 6-week follow-up	3.76±3.3	3.57±2.4	.776
Leg pain at 2-year follow-up	3.98±3.5	3.71±3.0	.686
Leg pain mean difference at 2-year follow-up	−1.43±3.9	−1.96±3.08	.458
Preoperative PROMs			
ODI	50.5±16.0	51.8±15.6	.713
SRS22r activity	2.5±0.8	2.4±0.8	.447
SRS22r pain	2.2±0.7	2±0.8	.234
SRS22r appearance	2.3±0.9	2.0±0.6	.084
SRS22r mental health	3.5±1.0	2.9±1.0	**.009**
SRS22r satisfaction	2.7±1.2	2.3±1.0	**.034**
SRS22r total score	2.6±0.6	2.3±0.6	**.026**
Mean change in PROMs at 2-year follow-up			
ODI	−13.2±20.2	−16.2±16.2	.434
SRS22r activity	0.7±0.9	1.0±1.0	.098
SRS22r pain	1.2±1	0.5±3.3	.141
SRS22r appearance	1.0±1.2	1.2±0.9	.392
SRS22r mental health	0.3±0.9	0.9±0.7	**.002**
SRS22r satisfaction	1.6±1.2	1.8±1.4	.426
SRS22r total score	0.9±0.7	1.1±0.7	.093
Perioperative variables			
Allotransfused blood units	3.2±3.3	3.9±5	.409
Transfused frozen plasma units	1.1±2.5	2.7±6.2	.103
EBL (ml)	2723±2022	2809±2152	.839
Operative duration (minutes)	470±163	459±174	.759
Colloids (ml)	771±849	763±906	.966
Crystalloid (ml)	4315±2604	3525±1782	.084
Extent of instrumentation (# of levels)	11.1±3.5	10.6±3.4	.421
LOS (days)	8.8±5.1	9.1±3.9	.756
Preoperative radiographic parameters			
SS°	24.6±11.3	25.0±10	.409
PT°	31.0±8.9	32.3±9.3	.233
PI°	55.5±10.7	57.4±11.1	.886
PI-LL° (mismatch)	34.7±11.8	36.8±16.7	.651
Segmental lordosis°	7.3±13.2	5.1±14.5	.425
L1-S1 lordosis°	20.8±14.4	20.5±17.7	.758
SVA (mm)	132.9±59.5	143.4±74.5	.685
Radiographic measurements mean change at 2-year follow-up			
SS°	8.1±9.2	8.3±6.9	.874
PT°	−8.3±8.9	−7.4±6.2	.561
PI°	−0.2±1.9	0.9±5.3	.152
PI-LL° (lumbar mismatch)	−31.1±12.9	−30.9±13.1	.917
Segmental lordosis°	28.7±9.5	32.9±9.6	**.038**
L1-S1 lordosis°	30.9±13.1	31.8±15.4	.765
SVA (mm)	−81.46±68.6	−91.5±65.6	.463

* All variables are presented as means ± standard deviations.

† Bold font indicates statistical significance.Abbreviations: BMI, body mass index; EBL, estimated blood loss; LEMS, Lower Extremity Motor Score; LL: lumbar lordosis; LOS, length of stay; ml, milliliters; ODI, Oswestry disability index; PI, pelvic incidence; PT, pelvic tilt; SRS, Scoliosis Research Society; SS, sacral slope; SVA, sagittal vertical axis.

Table 4
Preoperative, surgical, and postoperative characteristics comparing dichotomous outcomes in patients undergoing osteotomy with and without cage insertion[†]

Variables	Without cages (n=49)	With cages (n=48)	p-value[‡]
Women	32 (65.3)	28 (58.3)	.480
Current smoker	2 (4.1)	2 (4.2)	.983*
Vertebral level of the 3CO			
L1	1 (2)	0 (0)	.870[§]
L2	5 (10.2)	9 (18.8)	
L3	31 (63.3)	25 (52.1)	
L4	12 (24.5)	13 (27.1)	
L5	0 (0)	1 (2.1)	
ASA score			
1	0 (0)	1 (2.1)	.403[§]
2	18 (36.7)	21 (43.8)	
3	31 (63.3)	25 (52.1)	
4	0 (0)	1 (2.1)	
CCI score			
0	9 (18.4)	12 (25)	.517[§]
1	9 (18.4)	12 (25)	
2	12 (24.5)	10 (20.1)	
3	8 (16.3)	4 (8.3)	
4	5 (10.2)	2 (4.2)	
5	2 (4.1)	3 (6.3)	
6	4 (8.2)	5 (10.4)	
Surgical variables			
Previous spine surgery	43 (87.8)	45 (93.8)	.309
Previous spine fusion	35 (71.4)	44 (91.7)	**.010**
Satellite rods	20 (40.8)	14 (29.2)	.229
Accessory rods	16 (32.7)	21 (43.7)	.261
Anterior approach	3 (6.1)	7 (14.6)	.171
Use of BMP-2	38 (77.6)	31 (64.6)	.159
Postoperative surgical complications			
Overall complications	28 (57.1)	27 (56.3)	.929
Reoperation	13 (26.5)	15 (31.3)	.521
Postoperative motor deficit	3 (6.1)	4 (8.4)	.242*
PJK	7 (14.3)	8 (16.7)	.746
Dural tear	5 (10.2)	4 (8.3)	.973*
New postoperative radiculopathy	5 (10.2)	4 (8.3)	1.000*
Rod breakage	9 (18.4)	12 (25)	.428
Radiolucency	9 (18.4)	4 (8.3)	.147
Cardiopulmonary	4 (8.2)	4 (8.3)	.976*
Wound infection	4 (8.2)	3 (6.3)	.716*
2 years postoperative fusion			
Fusion	27 (55.1)	38 (79.2)	**.012**

* Fisher exact test.
† Values are presented as numbers and percentages; n (%).
‡ Bold font indicates statistical significance.
§ Linear by linear association.Abbreviations: 3CO, 3 column osteotomy; ASA, American Society of Anesthesiologists; BMP-2, bone morphogenetic protein; CCI, Charlson Comorbidty Index; PJK, proximal junctional kyphosis.

changes in postoperative lumbar parameters were found (Table 4).

Fusion and PROMs at 2 years of postoperative follow-up

A significantly higher number of patients in the group with cages achieved fusion at 2 years (79.2% vs. 55.1%, p=.012) (Table 4). In terms of postoperative PROMs at 2 years, the only difference between groups was in the mental health domain, with a significantly higher increase in the cages group (0.9±0.7 vs. 0.3±0.9, p=.002). No other differences were found in terms of SRS22r or ODI.

Regression analysis

We found that the use of an interbody cage at the osteotomy site was a significant independent predictor of improvement in segmental lordosis (p=.034) (Table 5). More importantly, we found that patients undergoing Schwab 4 osteotomies with cages and "sandwich" osteotomies had an OR of 3.3 (95% CI 1.108-10.05, p=.032) for achieving adequate fusion at the osteotomy site (Table 6).

Discussion

To our knowledge, this study represents the first direct comparison of Schwab 3 and Schwab 4 osteotomies,

Table 5
Multivariate linear regression analysis to determine predictors of mean change in segmental lordosis

Variable	ß coefficient	p-value*	95.0% CI for ß	
			Lower bound	Upper bound
Use of a cage at the osteotomy site	4.226	**.034**	0.318	8.134
Preoperative PI-LL (lumbar mismatch)	−0.080	.477	−0.304	0.143
Preoperative L1-S1 (lumbar lordosis)	−0.177	.056	−0.358	0.005
Preoperative SVA	0.032	.054	−0.001	0.065
Osteotomy level	−2.402	.078	−5.082	0.278
Age	−0.003	.977	−0.237	0.230
Previous spine fusion	−1.583	.526	−6.527	3.361

* Bold font indicates statistical significance.Abbreviations: CI, confidence interval; LL, lumbar lordosis; PI, pelvic incidence; SVA, sagittal vertical axis.

categorizing patients into 4 groups based on the use of interbody cages at the osteotomy site. The results of this retrospective analysis, derived from a prospectively maintained multicenter database, indicate that there are no statistically significant differences in morbidity between the 4 studied 3CO techniques. There were also no statistically significant longer lengths of hospital stay or higher rates of perioperative complications, blood loss, or prolonged surgical duration. Additionally, there were no differences in postoperative radiculopathy or neurological deficits between groups. Despite the absence of statistically significant differences between groups in multiple variables, no firm conclusion can be drawn about the direction or magnitude of the underlying differences. Nevertheless, these techniques may have conferred a clinically important positive or negative impact on the different variables studied, even in the absence of statistically significant differences.

Regarding radiographic outcomes at the 2-year follow-up, patients who underwent Schwab 4+cage procedures or "sandwich" osteotomies exhibited favorable, significantly greater mean changes in segmental lordosis and higher fusion rates at the osteotomy site. In linear regression analysis, the use of a cage emerged as a significant predictor for achieving better segmental lordosis; and in binary logistic regression analysis, the cage use was associated with higher rates of fusion at the osteotomy site at the 2-year mark. The improvement in lordosis could be attributed to a better fulcrum at the osteotomy site with the use of a cage, whereas the increased fusion rate could be explained by the enhanced stability at the osteotomy provided by the interbody cages and the supplementary fusion area.

Table 6
Multivariate logistic regression analysis to determine predictors of circumferential fusion

Variable	p-value*	OR	95% CI	
			Lower	Upper
Use of a cage at the osteotomy	**.032**	3.338	1.108	10.054
Satellite rod	.212	0.442	0.123	1.594
Accessory rod	.993	1.006	0.297	3.404
Women	.302	0.546	0.173	1.726
Previous spine surgery	.792	0.730	0.070	7.563
Previous spine fusion	.757	1.319	0.228	7.642
BMI	.196	0.947	0.872	1.029
CCI	.113	0.784	0.580	1.059
Current smoker	.419	0.319	0.020	5.093
ASA	.236	0.518	0.174	1.536
Anterior approach	.152	0.288	0.053	1.582
Length of instrumentation (n of levels)	.996	1.000	0.860	1.162
BMP-2	.544	1.480	0.417	5.244

* Bold font indicates statistical significance.Abbreviations and acronyms: ASA; American Society of Anesthesiologists Classification; BMI; body mass index; BMP, bone morphogenetic protein; CCI, Charlson Comorbidity Index; CI, confidence interval; n, number; OR, odds ratio.

Demographic and preoperative PROMs

Patients undergoing a "sandwich" osteotomy or Schwab 4+cage procedure were more likely to have a history of lumbar spine surgery, lumbar spine fusion, or both. This suggests that patients with more rigid deformities as a result of the previous surgeries are often offered and require more aggressive subsequent treatments to correct the spinal misalignment [29].

Interestingly, in our study groups, patients undergoing a "sandwich" osteotomy had significantly higher preoperative leg pain scores and overall lower preoperative SRS22r scores. Additionally, when patients undergoing Schwab 4 +cage and "sandwich" osteotomy techniques were grouped, they also had lower preoperative SRS22r scores, possibly indicating a worse preoperative condition. Lower preoperative SRS22r scores have been linked to increased rates of perioperative complications [30] and can act as confounding variables for severe comorbidities and preoperative disabilities, potentially influencing outcomes [30–32].

Perioperative variables, complications, and radiographic parameters

Despite being more aggressive surgical approaches, neither the Schwab 4+cage nor the "sandwich" osteotomy were associated with significantly higher rates of intraoperative bleeding, surgical duration, postoperative neurological radiculopathy, or motor deficits when compared to the traditional Schwab 3. This is particularly relevant because one

of the main complications after procedures involving 3COs is postoperative radiculopathy, with rates as high as 23.5% [33,34]. A lower rate was observed in our series, with a total postoperative radiculopathy rate of 9.2%.

The postoperative radiculopathy rate in our study is a finding that challenges the belief that patients undergoing more aggressive osteotomies might have higher rates of nerve root deficits [35]. Moreover, the concept of implanting a cage at the disc space or at the osteotomy site serves to improve fusion rates, facilitates deformity correction, and prevents severe spinal shortening and secondary root compression [36]. The use of an interbody implant increases the height and thereby enlarges the area of the foramen [37]. Several studies have shown that the use of a cage at the intervertebral disc increases segmental lordosis in degenerative spine surgery [38–41]. However, the effect of interbody cages at the osteotomy site for spinal deformity surgery in restoring segmental lordosis has been rarely reported [15,16]. Our series contributed to fill this gap by showing significant differences in terms of a mean change in postoperative segmental lordosis between the with and without cage groups, favoring the group with a cage at the osteotomy site but without significant changes in other lumbar sagittal alignment parameters, such as lumbar lordosis. The absence of a statistically significant postoperative difference in the mean change in overall lumbar lordosis between the groups could be attributed to the presence of stiffer spines in the osteotomy cage group, due to a higher frequency of prior fusion surgeries and more extensive history of bone fusion [17].

The rate of overall complications in our series, including medical and surgical complications, was 56.7%, with a reoperation rate of 28.8%, primarily driven by PJK and rod breakage. These findings are consistent with those documented by Mills et al. [42], who reported a complication rate of 57.8% in 675 patients who underwent PSO according to data from the PearlDiver database [42]. Bourghli et al. [43], reported an overall complication rate of 54.9% after PSO at L4 or L5 with a 22.5% revision rate during a mean follow-up of 49 months [43]. The heightened complication rates linked to 3COs may not solely stem from the procedure itself, but also from the surgical complexity inherent in patients undergoing revision surgeries [44]. Consistent with this observation, 81.4% of patients in our series had undergone previous spine fusions, amplifying surgical challenges due to scarring and prior osseous fusion [44–46]. Importantly, the incorporation of a cage at the osteotomy site or adjacent disc space did not correlate with any adverse outcomes in terms of complications in our series.

Fusion rates and mechanical complications

The use of interbody fusions to prevent pseudarthrosis and revision of iliac instrumentation in long surgical constructs has been extensively studied, especially at the L5S1 segment [47–49]. However, scarce information exists about using interbody cages at the osteotomy level to improve fusion rates. In one of the largest series published to date on Schwab 4 osteotomies, Buell et al. [16], did not find an association between the use of cages and the reduction of rod fractures and pseudarthrosis. Instead, those authors found that the use of multiple rod constructs was associated with a reduced occurrence of these complications [16].

Our univariate analysis demonstrated that patients who underwent osteotomy with the use of a cage were more likely to achieve satisfactory fusion at 2 years. In the multivariate analysis, we demonstrated that the use of a cage was an independent factor in obtaining adequate fusion. To our knowledge, this is the first study to show significant benefits of using cages at a PSO or with a Schwab 4 osteotomy to increase fusion rates and potentially reduce long-term complications.

It is important to acknowledge the grade of biomechanical instability associated with 3COs [19,20,50,46,50] and the possible consequences of nonunion, including severe pain, neurological deficit, and reoperation [19,20]. Our results showed that the use of a cage at the osteotomy level can reduce the risk of these complications. Schwab 3 and Schwab 4 techniques entail creating a "floating" vertebra that is detached from the posterior arch and isolated from the disc spaces of the superior and inferior vertebrae [46]. One repercussion of inducing this instability to rectify spinal malalignment is nonunion, often evidenced by rod breakage. The incorporation of cages enhances the stiffness of the anterior spine, thereby altering load distribution favorably and reducing stress on instrumentation [51]. This, in turn, promotes bone healing and fusion [51].

Although the utilization of cages positively influenced fusion rates, it did not correlate with a decrease in the rates of overall reoperation or rod breakage. This finding could be attributed to the constraint of analyzing reoperation and complication rates solely over a 2-year period. Furthermore, it is crucial to take into account factors beyond mechanical considerations, such as the biological aspects of fusion [52]. We integrated the use of BMP-2 into our analysis but found no discrepancy among the groups regarding its utilization, nor its use affect the multivariate analysis. Extended follow-up periods may be required to differentiate among groups concerning reoperation rates, as highlighted by Puvanesarajah et al. [53], The results of their study indicate that the rate of ASD revision increases from 10.5% within the first postoperative year to 18.5% within the initial 5 years [53].

Rod configuration did not emerge as an independent predictor for fusion in our series. This aligns with the findings of Dinizo et al. [54], who observed no disparity in fusion grade or occurrences of rod fracture, pseudarthrosis, or revision at 2 years after the utilization of either a 2-rod or multiple-rod construct in ASD revision cases for pseudoarthrosis [54]. Conversely, Hyun et al. [55], reported a decrease in rod breakage and revision surgery among patients with ASD who underwent 3CO; however, that finding was not

associated with an improvement in the fusion rate across the osteotomy [55].

Surgical implications

Although the use of a cage at the osteotomy site did not improve reoperation rates at the 2-year mark, the improved fusion rates associated with high-grade osteotomies using a cage suggest the potential for better long-term clinical outcomes beyond 2 years. This hypothesis, however, requires confirmation through further studies. Additionally, the fact that high-grade osteotomies with a cage were not associated with higher complication rates compared to traditional 3COs is an impactful finding. Spinal deformity surgeons could use this information to perform high-grade osteotomies with a cage in patients requiring better segmental lordosis correction, based on patient-specific alignment goals, without increasing complications or adverse events, compared to traditional 3COs.

Limitations and generalizability

This study has multiple limitations, including its retrospective nature and the limited follow-up duration of 2 years. The presence of fusion was determined solely based on X-rays. Additionally, the number of patients included in each group in our series is low, increasing the risk of a type II error, which could explain the absence of differences in other radiographic outcomes. Moreover, there might also be a risk of type I error and the possibility of inflated statistical findings. Therefore, these findings should be considered preliminary until larger independent studies provide corroboration. Another important limitation to consider is the presence of selection bias. Although the ideal scenario would involve having very similar cohorts of patients under the same baseline circumstances, this was not the case in this study and is not always the case in "real life." Typically, younger patients with worse malalignment, as seen in this study, are eligible for more aggressive procedures such as the Schwab 4+cage and "sandwich" osteotomy. Additionally, there may be bias in terms of surgical experience at various surgical centers, influenced by surgeon experience with different techniques and the results obtained with each technique. Despite providing evidence that using a cage at the lumbar 3CO site increases fusion rates without increasing clinical complications, a prospective trial comparing 3COs with and without cages at the level of the osteotomy is recommended.

Conclusion

Utilizing cages at the osteotomy site during a 3CO with the Schwab 4+cage or "sandwich" osteotomy increased the segmental lordosis at the osteotomy site and, more importantly, enhanced fusion rates at the osteotomy site without elevating overall complication rates in comparison to Schwab 3 and Schwab 4 without cage techniques.

Declaration of Competing Interest

One or more of the authors declare financial or professional relationships on ICMJE-TSJ disclosure forms.

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