

Very long-term outcomes of unilateral versus bilateral pedicle screw fixation with more than 10 years of follow-up

Xiaoyu Zhou

Shandong First Medical University

Erfu Dong

Shandong First Medical University

Wenting Zha

Shandong First Medical University

Yijie Kong

Shandong Second Medical University

Xiaoduo Xu

960th Hospital of PLA

Xin Chen

960th Hospital of PLA

Ziming Li

960th Hospital of PLA

Lei Wang

960th Hospital of PLA

Jingming Wang

960th Hospital of PLA

Weimin Huang

ever_23@163.com

960th Hospital of PLA

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Abstract

Purpose

To compare very long-term clinical and radiographic outcomes of unilateral pedicle screw fixation (UPSF) versus bilateral pedicle screw fixation (BPSF) after single-level transforaminal lumbar interbody fusion (TLIF), with particular attention to adjacent segment degeneration (ASD).

Methods

This retrospective cohort study included 157 patients with at least 10 years of follow-up (UPSF, $n = 78$; BPSF, $n = 79$). Patient-reported outcomes, satisfaction, residual symptoms, and reoperations were assessed. Long-term radiographic data were available for 56 patients (36 UPSF, 20 BPSF) and included fusion, cage migration, radiographic ASD, adjacent disc and facet degeneration, disc height, and lumbar lordosis. Propensity score matching yielded 17 radiographic pairs.

Results

Final back pain, leg pain, and Oswestry Disability Index scores were similar between groups after adjustment for the corresponding preoperative scores; satisfaction and residual symptoms were also comparable. Reoperation occurred in 3.8% of patients in each group. Fusion rates were 97.2% after UPSF and 95.0% after BPSF, with similar cage migration rates. Cranial radiographic ASD was less frequent after UPSF in both the full radiographic cohort (19.4% vs 45.0%, $P = .043$) and the matched cohort (17.6% vs 52.9%, $P = .031$). No significant between-group differences were observed in caudal ASD or grade-based disc and facet degeneration progression, and the longitudinal trajectories of disc height and lumbar lordosis were comparable between groups.

Conclusion

Beyond 10 years after single-level TLIF, UPSF and BPSF showed comparable patient-reported outcomes, reoperation rates, fusion, and index-level radiographic stability. UPSF was associated with less cranial radiographic ASD, without corresponding differences in patient-reported outcomes or reoperation.

Introduction

Lumbar degenerative disease is a major cause of low back pain, radiculopathy, and functional disability. Transforaminal lumbar interbody fusion (TLIF) is widely used when neural decompression and segmental stabilization are required[1]. Bilateral pedicle screw fixation (BPSF) provides rigid three-dimensional fixation but requires wider posterior exposure and may increase paraspinal muscle injury and adjacent-segment loading[2–4]. By preserving the contralateral osteoligamentous complex and muscular attachments, unilateral pedicle screw fixation (UPSF) may reduce surgical trauma while maintaining adequate stability in selected single-level procedures.

Previous comparisons have focused primarily on perioperative and short- to mid-term outcomes. UPSF has been associated with shorter operative time and less blood loss, while patient-reported outcomes, complications, and satisfaction have generally been similar to those after BPSF[5, 6]. However, the lower stiffness of the unilateral construct may permit greater segmental motion and implant stress, particularly during axial rotation and lateral bending, raising concerns regarding nonunion, cage migration, implant failure, and loss of alignment[7–9].

Comparative evidence beyond 10 years remains scarce, particularly for studies evaluating patient-reported outcomes together with fusion, implant-related events, adjacent disc and facet degeneration, disc height, and lumbar lordosis. We therefore compared very long-term clinical and radiographic outcomes after single-level TLIF with UPSF versus BPSF, with particular attention to index-level stability and cranial and caudal radiographic adjacent segment degeneration (ASD). Propensity score matching was used to address covariate imbalance in the radiographic subcohort.

Methods

Study population

Patients who underwent lumbar fusion with UPSF or BPSF at our institution between January 2011 and December 2015 were identified. Of 812 identified patients, 404 who underwent multilevel fusion were excluded, and the remaining 408 single-level TLIF cases were screened for eligibility (Fig. 1).

The inclusion criteria were as follows: (1) diagnosis of single-level lumbar spinal stenosis or lumbar disc herniation; (2) treatment with either unilateral or bilateral pedicle screw fixation; (3) a postoperative follow-up interval of at least 120 months with complete clinical data; and (4) no significant degeneration at non-fused lumbar levels on preoperative magnetic resonance imaging (MRI), defined as Pfirrmann grade ≤ 3 for intervertebral discs[10] and Fujiwara grade ≤ 2 for facet joints[11].

The exclusion criteria were as follows: (1) previous lumbar surgery or surgery performed for nondegenerative conditions, including infection, tumor, trauma, or severe spinal deformity, such as scoliosis with a Cobb angle $> 30^\circ$; (2) severe systemic disease, such as rheumatoid arthritis, Parkinson's disease, or severe osteoporosis, or psychiatric disorders precluding reliable follow-up; and (3) marked deterioration in physical function during follow-up due to other comorbidities, such as stroke, myocardial infarction, or malignancy.

Because this was a retrospective study with a predefined study period and a long-term follow-up requirement, the study size was determined by all eligible patients who completed at least 10 years of clinical follow-up; no a priori sample-size calculation was performed.

Surgical procedure

All patients underwent conventional single-level TLIF, including neural decompression, discectomy, endplate preparation, bone grafting, interbody cage placement, and pedicle screw fixation. Cage type and size were selected according to individual anatomy and intraoperative requirements. Fixation laterality was determined by the treating surgeon in routine clinical practice, and the principal procedural difference between groups was unilateral versus bilateral pedicle screw placement.

Clinical data collection and follow-up

Baseline demographic and clinical data, including age, sex, body mass index (BMI), smoking status, alcohol consumption, diabetes, diagnosis, and surgical level, were obtained from institutional records. Back and leg pain were assessed using visual analog scale (VAS) scores, and disability was assessed using the Oswestry Disability Index (ODI), preoperatively and at final follow-up. Residual symptoms were categorized as low back pain, leg numbness, both, or none. Patient satisfaction was graded according to the four-level North American Spine Society patient satisfaction index: grade 1, expectations completely met; grade 2, improvement below expectations but willing to undergo the same procedure again; grade 3, unwilling to undergo the same procedure again; and grade 4, no improvement or worsening[12]. Reoperations and their indications were recorded.

Final clinical outcomes were obtained through structured telephone interviews or outpatient visits. Patients were invited to undergo radiographic reassessment with anteroposterior and lateral lumbar radiographs and lumbar MRI. Data were collected using standardized case report forms and independently cross-checked by two researchers, with discrepancies adjudicated by a senior spine surgeon. This study was approved by the institutional ethics committee (approval No. 2026105). The requirement for informed consent was waived for the retrospective review of existing medical records and imaging data. Informed consent was obtained from all patients who participated in the long-term follow-up, and written informed consent was obtained from those who underwent additional radiographic assessment.

Propensity score matching

Because covariate imbalance was present in the radiographic cohort, patients were matched 1:1 using nearest-neighbor propensity score matching with a caliper of 0.02. Covariates were age, sex, BMI, surgical level, and follow-up duration. Matching was performed

using SPSS version 26.0 (IBM Corp, Armonk, NY, USA), and covariate balance was assessed using absolute standardized mean differences (SMDs), with values < 0.10 indicating adequate balance.

Radiographic assessment

Preoperative and final follow-up lumbar radiographs and MRI scans were independently reviewed by two spine surgeons who were not involved in the procedures and were blinded to clinical data. Continuous measurements were averaged between observers, whereas categorical or ordinal disagreements were resolved by consensus or third-reviewer adjudication. Measurements were performed using the picture archiving and communication system and ImageJ version 1.54r (National Institutes of Health, Bethesda, MD, USA). Interobserver and intraobserver reliability was evaluated using kappa statistics or intraclass correlation coefficients. Outcomes included index-level fusion, cage migration, cranial and caudal radiographic ASD, Pfirrmann disc grade, Fujiwara facet grade, adjacent-level disc height index (DHI), and lumbar lordotic Cobb angle. Patients with L5–S1 fusion were excluded from caudal-level analyses.

Cage migration was defined by the simultaneous presence of both of the following criteria: (1) posterior displacement of the radiopaque marker by more than 2 mm compared with the immediate postoperative radiograph; and (2) contact of the radiopaque marker with, or its location posterior to, the posterior border of either adjacent vertebral body[13]. Interbody fusion was defined as the absence of radiolucent lines, subsidence, or cystic changes at the implant–bone interface, together with continuous trabecular bone bridging across the intervertebral disc space, particularly in the posterior, lateral, interbody, or intradiscal regions.

Facet joint degeneration was graded according to the Fujiwara classification, and disc degeneration was graded according to the Pfirrmann classification. Adjacent segment degeneration was defined as an increase of at least one grade in the Pfirrmann classification at follow-up, an increase in segmental kyphosis of more than 5°, loss of disc height greater than 3 mm, or loss of disc height greater than 50%[14]. The DHI was calculated on lateral radiographs as the ratio of disc space height to the height of the superior vertebral body.

Statistical analysis

Normality was assessed using the Shapiro–Wilk test. Normally distributed continuous variables were compared using independent-samples t tests, and nonnormally distributed variables using Mann–Whitney U tests. Categorical outcomes in the full cohort were compared using chi-square or Fisher exact tests, as appropriate. Binary outcomes in the matched cohort were analyzed using two-sided exact McNemar tests; caudal analyses included only complete matched pairs with an evaluable caudal level. Satisfaction grades were compared using the Mann–Whitney U test.

Final back pain VAS, leg pain VAS, and ODI scores were compared using analysis of covariance, with the corresponding preoperative score entered as the covariate after confirmation of homogeneous regression slopes. Changes in disc height index and lumbar lordotic Cobb angle were evaluated using repeated-measures analysis of variance. Analyses were performed using SPSS version 26.0, with two-sided $P < .05$ considered statistically significant.

Results

Baseline characteristics

The patient selection process is shown in Fig. 1. Of 812 patients identified, 408 single-level cases were screened and 157 were included in the clinical cohort (78 UPSF and 79 BPSF). The UPSF group was younger than the BPSF group (46.04 ± 10.57 vs 50.37 ± 10.57 years; $P = .011$) and had a shorter follow-up duration (136.04 ± 11.57 vs 146.16 ± 18.96 months; $P < .001$); the remaining baseline characteristics were similar (Table 1). Reoperation occurred in 3 patients (3.8%) in each group. Indications were screw breakage in 2 patients and fusion failure in 1 after UPSF, and screw breakage in 1 and fusion failure in 2 after BPSF.

Table 1
Baseline, perioperative, and follow-up characteristics

	UPSF group (n = 78)		BPSF group (n = 79)		t	p value
	Mean ± SD		Mean ± SD			
Age at surgery (y)	46.04 ± 10.57		50.37 ± 10.57		-2.57	0.011
BMI (kg/m ²)	25.06 ± 2.36		24.78 ± 2.04		0.795	0.428
Length of hospital stay (d)	14.09 ± 4.16		14.92 ± 3.01		-1.433	0.154
Mean follow-up (mo)	136.04 ± 11.57		146.16 ± 18.96		-4.043	< 0.001
	n	%	n	%	χ ²	
Gender					2.29	0.13
Males	41	52.6	32	40.5		
Females	37	47.4	47	59.5		
Surgical level						0.083*
L1/2	0	0	1	1.3		
L3/4	5	6.4	3	3.8		
L4/5	53	67.9	42	53.2		
L5/S1	20	25.6	33	41.7		
Smoking status					2.32	0.314
Nonsmoker	52	66.7	61	77.2		
Current smoker	16	20.5	10	12.7		
Former smoker	10	12.8	8	10.1		
Diabetes					0.55	0.458
Yes	7	9.0	10	12.7		
No	71	91.0	69	87.3		
Alcohol consumption					1.51	0.219
Yes	19	24.4	13	16.5		
No	59	75.6	66	83.5		
Reoperation	3	3.8	3	3.8		1.000*
Fusion failure	1	1.3	2	2.5		
Screw breakage	2	2.6	1	1.3		
*Exact test. Fisher–Freeman–Halton exact test was used for surgical level, and Fisher’s exact test was used for reoperation. UPSF: unilateral pedicle screw fixation; BPSF: bilateral pedicle screw fixation; BMI: body mass index.						

The radiographic subcohort included 36 UPSF and 20 BPSF patients. Propensity score matching yielded 17 pairs and improved overall covariate balance, although residual imbalance remained for follow-up duration (SMD, 0.121) and surgical level (SMD, 0.371) (Table 2).

Table 2
Characteristics and covariate balance of the radiographic cohort before and after propensity score matching

	Before		Standardized Mean Difference	After		
	UPSF group (n = 36)	BPSF group (n = 20)		UPSF group (n = 17)	BPSF group (n = 17)	Standardized Mean Difference
Age at surgery, years	52.0 ± 7.02	48.9 ± 9.25	0.377	48.2 ± 6.10	47.9 ± 8.25	0.041
Gender, Male/Female	20/16	7/13	0.417	7/10	7/10	0.000
BMI, kg/m ²	25.37 ± 2.72	24.75 ± 2.75	0.227	24.86 ± 1.75	24.70 ± 2.42	0.076
Follow-up duration, months	147.81 ± 12.09	164.65 ± 21.23	0.974	153.12 ± 10.58	154.71 ± 15.21	0.121
Surgical level			1.027			0.371
L1/2	0	1		0	0	
L3/4	1	3		1	1	
L4/5	19	15		13	15	
L5/S1	16	1		3	1	
Values are presented as mean ± standard deviation or number. SMDs are absolute values, with SMD < 0.10 indicating adequate balance. For surgical level, the maximum absolute category-specific SMD is reported. <i>UPSF</i> , unilateral pedicle screw fixation; <i>BPSF</i> , bilateral pedicle screw fixation; <i>BMI</i> , body mass index; <i>SMD</i> , standardized mean difference.						

Patient-reported outcomes

Residual symptoms did not differ between groups ($P = .096$). Satisfaction grades were also similar ($P = .957$), with favorable ratings (grades 1 or 2) in 93.6% of UPSF and 88.6% of BPSF patients. Both groups showed substantial improvements in VAS and ODI scores. After adjustment for the corresponding preoperative scores, no between-group differences were detected in final back pain VAS ($P = .701$), leg pain VAS ($P = .994$), or ODI ($P = .231$) (Table 3).

Table 3
Clinical outcomes before surgery and at final follow-up

	No. of Patients (%)		
	UPSF group (n = 78)	BPSF group (n = 79)	p value
Residual symptoms			0.096
None	57(73.1%)	52(65.8%)	
Low back pain	6(7.7%)	16(20.3%)	
Leg numbness	11(14.1%)	6(7.6%)	
Both	4(5.1%)	5(6.3%)	
Satisfaction index			0.957
1	45(57.7%)	47(59.5%)	
2	28(35.9%)	23(29.1%)	
3	4(5.1%)	7(8.9%)	
4	1(1.3%)	2(2.5%)	
Back pain VAS			0.701
Pre-operation	6.64 ± 1.41	6.53 ± 1.37	0.616
Final follow-up	0.77 ± 0.66	0.81 ± 0.75	0.712
Leg pain VAS			0.994
Pre-operation	7.13 ± 0.89	7.23 ± 1.13	0.547
Final follow-up	0.88 ± 0.79	0.90 ± 0.73	0.908
ODI			0.231
Pre-operation	68.04 ± 12.86	69.20 ± 9.75	0.440
Final follow-up	12.86 ± 5.18	13.90 ± 5.14	0.211
P values shown on the VAS and ODI heading rows were derived from ANCOVA adjusted for the corresponding preoperative score; P values in the preoperative and final follow-up rows represent unadjusted between-group comparisons. <i>UPSF</i> : unilateral pedicle screw fixation; <i>BPSF</i> : bilateral pedicle screw fixation; <i>VAS</i> : visual analog scale; <i>ODI</i> : Oswestry Disability Index.			

Radiographic outcomes: full radiographic cohort analysis

Fusion was achieved in 35 of 36 UPSF patients (97.2%) and 19 of 20 BPSF patients (95.0%; $P = 1.000$). Cage migration occurred in 3 of 36 (8.3%) and 1 of 20 (5.0%), respectively ($P = 1.000$). Cranial radiographic ASD was more frequent after BPSF (45.0% vs 19.4%; $P = .043$), whereas caudal ASD did not differ among patients with an evaluable caudal level (15.8% vs 25.0%; $P = .695$) (Table 4).

Table 4
Radiographic outcomes in the full radiographic cohort

	Pre-operation				Final follow-up				Interaction (<i>P</i> , η^2)		
	UPSF group (n = 36)		BPSF group (n = 20)		p	UPSF group (n = 36)		BPSF group (n = 20)		p	
	<i>n / Mean ± SD</i>	%	<i>n / Mean ± SD</i>	%		<i>n / Mean ± SD</i>	%	<i>n / Mean ± SD</i>			%
Fusion rate						35/36	97.2	19/20	95.0	1.00*	
Cage migration						3/36	8.3	1/20	5.0	1.00*	
Radiographic ASD											
Cranial level						7/36	19.4	9/20	45.0	0.043	
Caudal level‡						5/20	25.0	3/19	15.8	0.695*	
Cobb angle	37.34 ± 7.30		39.56 ± 7.27			35.96 ± 7.84		37.81 ± 7.53		(0.815, 0.001)	
Disc height index											
Cranial level	0.41 ± 0.08		0.43 ± 0.063			0.39 ± 0.06		0.40 ± 0.064		(0.604, 0.005)	
Caudal level	0.37 ± 0.09		0.38 ± 0.065			0.36 ± 0.10		0.39 ± 0.073		(0.383, 0.021)	
Pfirschmann grade(cranial)					0.303†					0.933†	
1	3	8.3				1	2.8				
2	20	55.6	17	85.0		8	22.2	4	20.0		
3	13	36.1	3	15.0		17	47.2	12	60.0		
4						8	22.2	3	15.0		
5						2	5.6	1	5.0		
Change in Grade										0.249*	
No change(Δ = 0)						16	44.4	5	25.0		
Progression (Δ ≥ 1)						20	55.6	15	75.0		
Pfirschmann grade(caudal)‡					0.860†					0.910†	
1	2	10.0									
2	10	50.0	12	63.2		4	20.0	3	15.8		
3	8	40.0	7	36.8		12	60.0	12	63.2		
4						2	10.0	4	21.1		
5						2	10.0				
Change in Grade										1.000*	
*Fisher's exact test. †Mann-Whitney U test for comparison between groups. ‡Patients with L5/S1 segment were excluded for the analysis of caudal levels. Change = final follow-up–preoperative. DHI: disc height index; UPSF: unilateral pedicle screw fixation; BPSF: bilateral pedicle screw fixation. η^2 : partial eta-squared.											

	Pre-operation				Final follow-up						
	UPSF group (n = 36)		BPSF group (n = 20)		p	UPSF group (n = 36)		BPSF group (n = 20)		p	Interaction (<i>P</i> , η^2)
	<i>n / Mean ± SD</i>	%	<i>n / Mean ± SD</i>	%		<i>n / Mean ± SD</i>	%	<i>n / Mean ± SD</i>	%		
No change(Δ = 0)						8	40.0	7	36.8		
Progression ($\Delta \geq 1$)						12	60.0	12	63.2		
Fujiwara grade(cranial)					1.000†					0.730†	
0	7	19.4	2	10.0		3	8.3				
1	22	61.1	16	80.0		15	41.7	9	45.0		
2	7	19.4	2	10.0		14	38.9	10	50.0		
3						4	11.1	1	5.0		
Change in grade										0.785*	
No change (Δ = 0)						18	50.0	9	45.0		
Progression ($\Delta \geq 1$)						18	50.0	11	55.0		
Fujiwara grade(caudal)‡					0.014†					0.202†	
0			1	5.3							
1	11	55.0	16	84.2		6	30.0	10	52.6		
2	9	45.0	2	10.5		13	65.0	8	42.1		
3						1	5.0	1	5.3		
Change in grade										0.191*	
No change (Δ = 0)						15	75.0	10	52.6		
Progression ($\Delta \geq 1$)						5	25.0	9	47.4		
*Fisher's exact test. †Mann-Whitney U test for comparison between groups. ‡Patients with L5/S1 segment were excluded for the analysis of caudal levels. Change = final follow-up–preoperative. DHI: disc height index; UPSF: unilateral pedicle screw fixation; BPSF: bilateral pedicle screw fixation. η^2 : partial eta-squared.											

Table 5
Radiographic outcomes in the propensity score-matched subcohort

	Pre-operation				Final follow-up				Time×Group Interaction	
	UPSF group (n = 17)		BPSF group (n = 17)		p	UPSF group (n = 17)		BPSF group (n = 17)		p
	<i>n / Mean ± SD</i>	%	<i>n / Mean ± SD</i>	%			<i>n / Mean ± SD</i>	%	<i>n / Mean ± SD</i>	
Fusion rate						16/17	94.1	16/17	94.1	1.000*
Cage migration						2/17	11.8	1/17	5.9	1.000*
Radiographic ASD										
Cranial level						3/17	17.6	9/17	52.9	0.031*
Caudal level‡						4/14	28.6	3/14	21.4	1.000*
Cobb angle	38.059 ± 8.019		40.013 ± 7.749			36.927 ± 7.506		38.444 ± 7.925		(0.788, 0.002)
Disc height index										
Cranial level	0.41 ± 0.079		0.42 ± 0.063			0.39 ± 0.052		0.40 ± 0.069		(0.944, < 0.001)
Caudal level‡	0.37 ± 0.093		0.37 ± 0.074			0.36 ± 0.115		0.38 ± 0.075		(0.291, 0.038)
Pfirrmann grade(cranial)					0.262†					0.534†
1	3	17.6								
2	6	35.3	15	88.2		2	11.8	2	11.8	
3	8	47.1	2	11.8		9	52.9	11	64.7	
4						4	23.5	3	17.6	
5						2	11.8	1	5.9	
Change in Grade										1.000*
No change(Δ = 0)						5	29.4	4	23.5	
Progression (Δ ≥ 1)						12	70.6	13	76.5	
Pfirrmann grade(caudal)‡					0.686†					0.944†
1	1	7.1								
2	9	64.3	11	68.8		4	28.6	2	12.5	
3	4	28.6	5	31.3		6	42.9	12	75.0	
4						2	14.3	2	12.5	

*Binary outcomes were compared using the two-sided exact McNemar test. †Mann-Whitney U test for between-group comparisons. ‡Patients who underwent L5-S1 fusion were excluded from caudal analyses; Caudal grade distributions were based on all evaluable patients (UPSF, n = 14; BPSF, n = 16), whereas binary caudal outcomes analyzed using the exact McNemar test included 14 complete matched pairs. Change = final follow-up - preoperative. DHI, disc height index; UPSF, unilateral pedicle screw fixation; BPSF, bilateral pedicle screw fixation; η^2 , partial eta squared.

	Pre-operation				Final follow-up				Time×Group Interaction		
	UPSF group (n = 17)		BPSF group (n = 17)		p	UPSF group (n = 17)		BPSF group (n = 17)		p	
	n / Mean ± SD	%	n / Mean ± SD	%		n / Mean ± SD	%	n / Mean ± SD	%		(P, η²)
5						2	14.3				
Change in Grade											1.000*
No change(Δ = 0)						5	35.7	6	42.9		
Progression (Δ ≥ 1)						9	64.3	8	57.1		
Fujiwara grade(cranial)						0.358†					0.352†
0	2	11.8	2	11.8		1	5.9				
1	10	58.8	13	76.5		5	29.4	8	47.1		
2	5	29.4	2	11.8		7	41.2	8	47.1		
3						4	23.5	1	5.9		
Change in grade											0.727*
No change (Δ = 0)						7	41.2	9	52.9		
Progression (Δ ≥ 1)						10	58.8	8	47.1		
Fujiwara grade(caudal)‡						0.023†					0.376†
0			1	6.3							
1	7	50.0	13	81.3		4	28.6	8	50.0		
2	7	50.0	2	12.5		10	71.4	7	43.8		
3								1	6.3		
Change in grade											0.219*
No change (Δ = 0)						11	78.6	7	50.0		
Progression (Δ ≥ 1)						3	21.4	7	50.0		
*Binary outcomes were compared using the two-sided exact McNemar test. †Mann–Whitney U test for between-group comparisons. ‡Patients who underwent L5–S1 fusion were excluded from caudal analyses; Caudal grade distributions were based on all evaluable patients (UPSF, n = 14; BPSF, n = 16), whereas binary caudal outcomes analyzed using the exact McNemar test included 14 complete matched pairs. Change = final follow-up – preoperative. DHI, disc height index; UPSF, unilateral pedicle screw fixation; BPSF, bilateral pedicle screw fixation; η², partial eta squared.											

No significant time-by-group interaction was observed for lumbar lordosis, DHI, or caudal DHI. Cranial DHI decreased over time across the cohort (P = .007), but its trajectory did not differ by fixation strategy. Apart from a higher preoperative caudal Fujiwara grade in the UPSF group, disc- and facet-grade distributions and grade-based progression rates were similar between groups (Table 4).

Radiographic outcomes: matched cohort analysis

The matched cohort analysis was consistent with the findings in the full radiographic cohort. Cranial radiographic ASD occurred significantly more frequently in the BPSF group than in the UPSF group (9/17 [52.9%] vs 3/17 [17.6%]; $P = .031$), whereas caudal radiographic ASD did not differ significantly between groups among the 14 evaluable matched pairs (3/14 [21.4%] vs 4/14 [28.6%]; $P = 1.000$). Repeated-measures analysis of variance showed no significant time-by-group interactions for the Cobb angle, cranial adjacent-segment DHI, or caudal adjacent-segment DHI (Cobb angle: $P = .788$, $\eta^2 = .002$; cranial DHI: $P = .944$, $\eta^2 < 0.001$; caudal DHI: $P = .291$, $\eta^2 = 0.038$). Thus, the long-term trajectories of lumbar lordosis and adjacent-segment disc height remained comparable between groups after matching.

After matching, Mann–Whitney U tests showed that, except for a persistently higher preoperative caudal facet Fujiwara grade in the unilateral fixation group ($P = .023$), no significant between-group differences were observed in the remaining preoperative or postoperative Pfirrmann or Fujiwara grades (all $P > 0.05$). When degenerative progression was defined as an increase of at least one grade from baseline to follow-up, two-sided exact McNemar tests showed no significant between-group differences in progression of the cranial disc (70.6% vs 76.5%; $P = 1.000$), caudal disc (64.3% vs 57.1%; $P = 1.000$), cranial facet joint (58.8% vs 47.1%; $P = .727$), or caudal facet joint (21.4% vs 50.0%; $P = .219$).

Representative cases

For descriptive illustration of the longitudinal imaging assessment and long-term postoperative appearance, serial images from one patient in each fixation group are presented. These cases are provided as clinical examples and are not intended for direct comparison between fixation strategies.

The first patient was a 43-year-old woman with L4–5 lumbar disc herniation associated with left-sided radicular pain and sensory disturbance. She underwent single-level L4–5 transforaminal lumbar interbody fusion with left-sided unilateral pedicle screw fixation. At the 10-year follow-up, the leg pain visual analog scale score decreased from 8 to 1, the Oswestry Disability Index improved from 64% to 14%, and the sensory disturbance had resolved. Serial radiographic and magnetic resonance imaging findings are presented in Fig. 2.

The second patient was a 42-year-old man with L4–5 lumbar disc herniation and left-sided radicular symptoms. He underwent single-level L4–5 transforaminal lumbar interbody fusion with bilateral pedicle screw fixation. At the final follow-up of more than 10 years, the leg pain visual analog scale score decreased from 7 to 1 and the Oswestry Disability Index improved from 58% to 12%. Corresponding longitudinal imaging findings are shown in Fig. 3.

Discussion

In this study, UPSF and BPSF combined with single-level TLIF yielded similar clinical outcomes and index-level radiographic stability beyond 10 years. The only consistent between-group difference was a higher incidence of cranial radiographic ASD after BPSF in both the full and propensity score–matched radiographic cohorts. Because patient-reported outcomes and reoperation rates were similar, this finding should be interpreted as a radiographic association rather than evidence of clinical superiority.

Long-term clinical comparability of unilateral fixation

Our findings showed comparable long-term VAS, ODI, and satisfaction outcomes between UPSF and BPSF. This finding is consistent with previous short- and mid-term studies[5, 6]. In a randomized controlled trial by Li et al., 32 patients undergoing single-level TLIF received UPSF and 34 received BPSF; at 12 months, VAS scores, ODI scores, and fusion rates did not differ significantly between groups[6]. Similar results were reported by Liu et al. in a larger cohort with longer follow-up: 109 UPSF patients and 106 BPSF patients completed at least 4 years of follow-up, and postoperative VAS scores, ODI scores, Japanese Orthopaedic Association scores, and fusion rates remained comparable at all follow-up time points[15]. These data suggest that satisfactory functional recovery can be achieved with either strategy: UPSF preserves the contralateral posterior structures, whereas BPSF provides greater initial construct stability. Our findings extend this evidence to follow-up beyond 10 years and support the durable clinical performance of UPSF.

Patient satisfaction showed a similar pattern. Although the proportion of patients with favorable satisfaction grades (grades 1 or 2) was slightly higher in the UPSF group, the overall distribution did not differ significantly from that in the BPSF group. From the standpoint of surgical invasiveness, BPSF generally requires wider bilateral detachment of paraspinal muscle insertions, which may prolong operative time and increase intraoperative blood loss. Such tissue trauma may also increase perioperative morbidity and

contribute to denervation injury and postoperative atrophy of key stabilizing muscles, particularly the multifidus[16, 17], potentially leading to persistent low back pain and functional impairment[18]. Nevertheless, most previous short- and mid-term studies, as well as the present study, did not demonstrate significant between-group differences in postoperative VAS scores, ODI scores, or satisfaction. In other words, the muscle-preserving advantage of UPSF may not be fully reflected in long-term patient-perceived outcomes.

One possible explanation is that the early benefit of reduced surgical trauma becomes attenuated over time. Once bleeding, muscle detachment, and other acute surgical injuries have healed, long-term function may depend more on fusion stability, adjacent-segment changes, aging-related musculoskeletal decline, and neuromuscular compensation than on the initial extent of muscle dissection alone. The lumbar paraspinal muscles, including the multifidus and deep stabilizing muscles, have a certain compensatory reserve for maintaining segmental stability, which may partly explain why the BPSF group did not show worse long-term functional outcomes despite wider muscle dissection[19].

Long-term safety comparability

The durability of UPSF relative to BPSF remains incompletely defined, largely because existing comparative studies have been limited by insufficient follow-up. The reoperation rate is an important endpoint for evaluating surgical safety, but its interpretation depends heavily on follow-up duration. The causes of revision also vary over time: early revisions are usually related to technical or perioperative factors, such as cage migration, infection, or neural injury, whereas later revisions are more often caused by ASD, pseudarthrosis, or instrumentation failure[20, 21]. Because most previous meta-analyses and clinical studies have reported follow-up periods of only 2 to 5 years[20, 22], they may underestimate the cumulative revision burden and fail to capture the transition from early clinical stability to delayed mechanical or degenerative failure. Studies with follow-up beyond 10 years are therefore essential for determining whether UPSF provides durable fixation and reliable safety.

Existing evidence suggests that the postoperative fusion rate after UPSF may be slightly lower than that after BPSF, with a reported difference of approximately 5%–10%[23]. However, most studies have not shown a statistically significant difference, and the clinical relevance of this finding remains debated. In a meta-analysis by Zhong et al., the fusion rate at final follow-up was lower in the UPSF group than in the BPSF group (RR = 0.95, 95% CI 0.91–1.00, $P = .041$)[24]. Notably, the included studies had follow-up durations of only 12–60 months, with most concentrated within 12–24 months after surgery; the authors also noted that the limited follow-up was insufficient to adequately evaluate long-term complications. Therefore, differences in fusion rates derived from short- or mid-term follow-up may not fully reflect the long-term stability of the fusion status.

Fusion assessment is also time dependent. Early radiographic evaluation may overestimate fusion success, as pseudarthrosis, cage subsidence, or fatigue failure of the instrumentation can become apparent only years after surgery. Conversely, some patients with pseudarthrosis may remain asymptomatic for prolonged periods, with functional stability maintained by fibrocartilaginous healing, scar tissue support, or the internal fixation construct[25]. These observations suggest that radiographic fusion and clinical outcomes do not have a simple linear relationship. Solid fusion reflects successful biological healing, but it does not necessarily indicate restoration of the biomechanical environment or symptomatic improvement. Therefore, long-term efficacy and safety should not be inferred from fusion rate alone, but should be evaluated together with patient-reported outcomes, reoperation rate, and radiographic stability.

With more than 10 years of follow-up, the present study allowed a more reliable assessment of delayed fusion, pseudarthrosis, instrumentation failure, late revision, and other safety-related outcomes. In this cohort, the reoperation rate beyond 10 years was 3.8% in both groups (3/78 in the UPSF group and 3/79 in the BPSF group), which was lower than the long-term reoperation rate of 5%–15% reported after lumbar fusion in previous studies[26]. All patients in the present study underwent single-level fusion. A 2026 meta-analysis including 10 studies and 1430 patients reported that single-level fusion was associated with a 41% lower revision risk than multilevel fusion (RR = 0.59, $P = .007$)[27]. In addition, the strict inclusion and exclusion criteria used in this study excluded several potential high-risk factors, including previous lumbar surgery, severe osteoporosis, severe spinal deformity, and serious systemic disease, thereby resulting in a cohort with a relatively low baseline risk of revision. In this context, the identical long-term reoperation rates in the two groups not only support the long-term safety of UPSF, but also provide a relatively balanced basis for comparing the long-term stability of the two fixation strategies.

Regarding the distribution of reoperation causes, the UPSF group had two cases of screw breakage and one case of fusion failure, whereas the BPSF group had one case of screw breakage and two cases of fusion failure. Given the very small number of revision

events, with only six cases in total, meaningful statistical comparison of revision-cause distribution between groups was not feasible, and the clinical implications should be interpreted with caution. This difference may simply reflect random variation, although it could also be related to the distinct biomechanical environments created by the two fixation strategies. The asymmetric load-sharing pattern of UPSF may increase stress concentration on the unilateral screw construct, whereas the wider paraspinal muscle dissection required for BPSF may compromise local blood supply and the fusion environment. However, these explanations remain speculative because they are based on a limited number of events and should not be regarded as definitive conclusions. Future studies with larger cohorts, long-term follow-up, and standardized documentation of revision causes are needed to clarify the potential relationships between fixation strategy and pseudarthrosis, instrumentation failure, and ASD-related revision.

Association of unilateral fixation with lower cranial radiographic ASD

ASD is one of the most important long-term radiographic concerns after lumbar fusion. Its development is multifactorial and may be influenced by age, BMI, preexisting adjacent-level degeneration, sagittal alignment, facet joint violation, paraspinal muscle condition, and fusion-related biomechanical remodeling[28, 29]. In the present study, cranial radiographic ASD occurred more frequently after BPSF in both the full and matched radiographic cohorts, whereas no significant difference was observed at the caudal adjacent segment. Thus, the observed association between fixation strategy and ASD appeared to be localized primarily to the cranial level.

This finding is consistent with the natural history of ASD and with previous long-term evidence. Both radiographic progression and symptom development in ASD are typically delayed, and short- to mid-term follow-up may therefore underestimate its true incidence. Most previous studies comparing UPSF and BPSF have focused primarily on fusion rate, pain scores, functional outcomes, and perioperative parameters, with limited assessment of ASD as a long-term endpoint[9, 21]. In a study with more than 10 years of follow-up, Kim et al. reported a lower incidence of radiographic ASD in the unilateral fixation group than in the bilateral fixation group (25.4% vs. 48.9%, $P = .035$), with a significant difference also observed at the second cranial adjacent segment ($P = .004$)[30]. These results are directionally consistent with our findings. However, because the study by Kim et al. was based on posterolateral fusion rather than contemporary interbody fusion techniques such as TLIF or posterior lumbar interbody fusion (PLIF), and because its radiographic assessment was relatively limited, it should be regarded as mechanistically supportive evidence rather than evidence that can be directly extrapolated to the present setting.

From a biomechanical perspective, bilateral fixation provides greater initial construct stiffness, but it may also increase the stiffness gradient between the fused segment and adjacent mobile segments, thereby shifting greater stress, motion, and intradiscal pressure to the adjacent levels. Previous studies have identified superior facet joint violation as an important surgery-related risk factor for ASD[29], and bilateral facet joint violation may further accelerate disc and facet degeneration at the cranial adjacent segment[31]. By contrast, unilateral fixation may preserve adequate index-level stability while retaining the contralateral posterior osteoligamentous complex, perifacet structures, and paraspinal muscle attachments, thereby reducing the abrupt biomechanical transition between the fused and adjacent segments. Recent finite element studies also support the concept that different posterior fixation strategies can alter stress distribution at adjacent segments[31].

In the present study, the difference in ASD was mainly localized to the cranial adjacent segment, which is consistent with the biomechanical load distribution after lumbar fusion. After single-level fusion, the cranial adjacent segment typically bears greater compensatory motion and shear stress, whereas the caudal segment, particularly after lower lumbar fusion, is often close to the lumbosacral junction and has relatively limited residual mobility. In this study, the cranial adjacent-segment disc height index (DHI) showed a significant main effect of time ($P = .007$, partial $\eta^2 = 0.128$), whereas the caudal DHI showed no significant temporal change ($P = .906$), further supporting the greater susceptibility of the cranial segment to long-term remodeling. Meanwhile, the time-by-group interactions for cranial DHI, caudal DHI, and lumbar lordotic Cobb angle were not statistically significant, indicating that unilateral fixation did not increase the long-term risk of adjacent-segment disc height loss or inadequate maintenance of lumbar lordosis despite its lower construct rigidity.

The postoperative Pfirrmann and Fujiwara grade distributions and grade-based progression rates were generally similar between groups. This does not necessarily contradict the difference in cranial radiographic ASD because ASD was defined as a composite endpoint incorporating disc-grade progression, segmental kyphosis, and disc-height loss. A patient could therefore meet the ASD definition through structural changes not fully reflected by a categorical shift in a single ordinal classification. In addition, the Pfirrmann and Fujiwara systems are relatively coarse grading scales and may have limited sensitivity for mild cumulative change. The small radiographic cohort also limited statistical power for detecting differences in individual disc- and facet-degeneration outcomes.

Consequently, the ASD result should be interpreted as an exploratory risk signal rather than definitive evidence that all components of adjacent-segment degeneration differ between fixation strategies.

Importantly, the difference observed in this study concerned radiographic ASD rather than a clearly established difference in symptomatic ASD. Although cranial radiographic ASD occurred significantly more frequently in the BPSF group in both the full and matched radiographic cohorts, VAS scores, ODI scores, patient satisfaction, and reoperation rates at the final follow-up did not differ significantly between groups, suggesting that some radiographic degeneration may remain clinically silent for a prolonged period[32]. Therefore, the present findings should not be interpreted as evidence that unilateral fixation definitively reduces symptomatic ASD or long-term revision risk. Rather, in carefully selected patients undergoing single-level TLIF, unilateral fixation may be associated with a lower risk of cranial radiographic ASD without compromising fusion rate, cage stability, or long-term clinical outcomes. This potential advantage should be further validated in larger prospective studies incorporating standardized computed tomography (CT) and MRI assessment, sagittal alignment parameters, paraspinal muscle evaluation, and symptomatic ASD endpoints.

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Limitations

First, owing to the retrospective design, residual confounding could not be completely eliminated. In the full clinical cohort, age and follow-up duration differed between groups, whereas the ANCOVA models for VAS and ODI adjusted only for the corresponding preoperative score. Therefore, residual confounding by age and follow-up duration cannot be excluded, and the clinical comparisons should be interpreted as baseline score-adjusted rather than fully confounder-adjusted estimates. Although propensity score matching substantially improved covariate balance, some residual imbalance remained in follow-up duration and surgical level. Given the limited radiographic sample, more restrictive matching would have further reduced sample size and statistical power. Second, considerable attrition occurred during the extended follow-up, particularly for standardized radiographic reassessment. Although 157 patients had complete long-term clinical data, only 56 (35.7%) had sufficiently complete radiographic data, and propensity score matching further reduced the sample to 34 patients (17 matched pairs). The limited sample size reduced statistical precision and power, increased the possibility of type II error, and precluded robust analysis of infrequent outcomes. Moreover, patients who completed long-term imaging follow-up may not have been fully representative of the overall cohort, introducing potential attrition bias. Therefore, the radiographic ASD findings should be considered exploratory despite their consistency across the full and matched cohorts and require confirmation in larger prospective studies with standardized long-term imaging follow-up. Third, fusion status was assessed mainly on radiographs, and CT data were unavailable for some patients, which may have introduced bias in the evaluation of fusion.

Conclusions

After more than 10 years of follow-up, UPSF and BPSF after single-level TLIF showed similar patient-reported outcomes, fusion rates, reoperation rates, and index-level radiographic stability. UPSF was associated with less cranial radiographic ASD, but without demonstrable differences in symptomatic ASD or reoperation. This exploratory association requires prospective confirmation.

Declarations

Author Contribution

X.Z. contributed to methodology, investigation, data curation, formal analysis, preparation of figures and tables, and writing of the original draft. E.D. and W.Z. contributed to investigation, data curation, and visualization. Y.K. and X.X. contributed to data curation, formal analysis, and software. X.C., Z.L., and L.W. contributed to validation and data curation. J.W. supervised and validated the study and reviewed and edited the manuscript. W.H. conceptualized the study, acquired funding, contributed to validation, and reviewed and edited the manuscript. All authors reviewed and approved the final manuscript.

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Figures

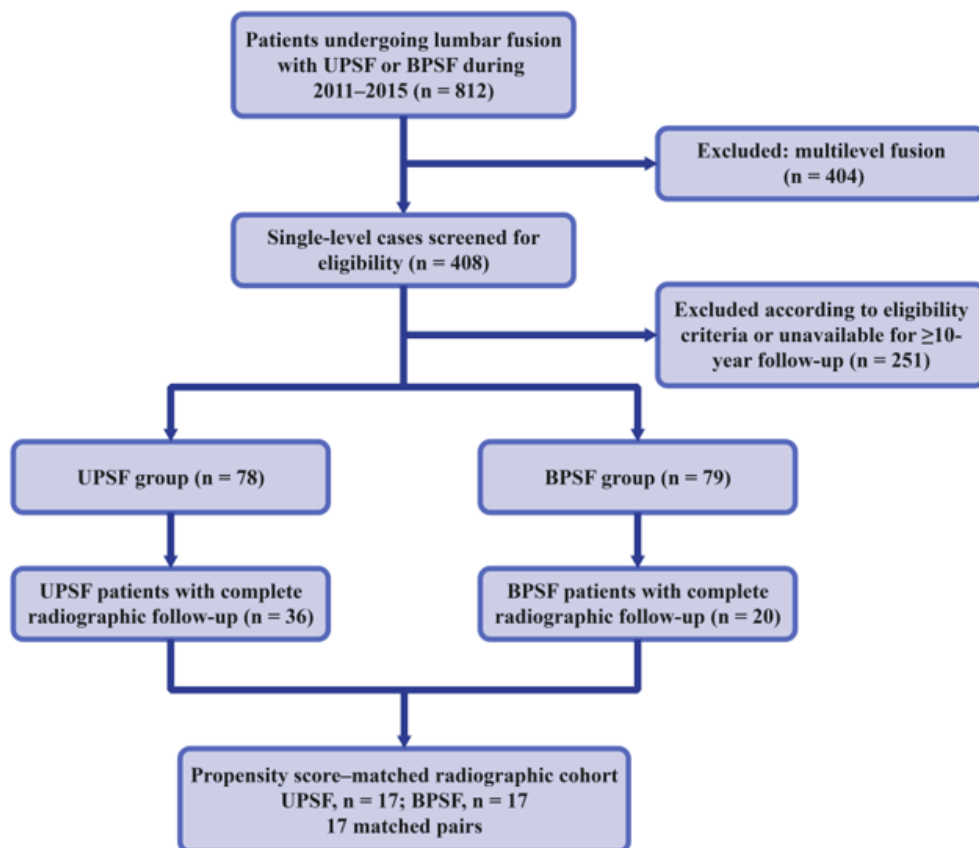


Figure 1

Flow diagram of patient selection and propensity score matching.

UPSF, unilateral pedicle screw fixation; BPSF, bilateral pedicle screw fixation.

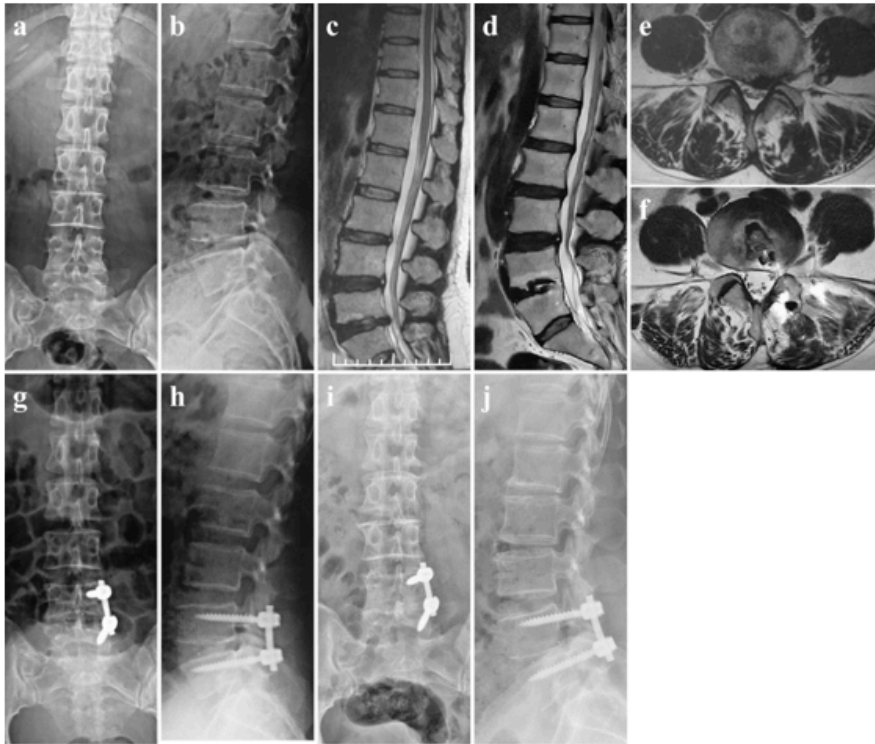


Figure 2

Serial imaging of a representative patient treated with L4–5 transforaminal lumbar interbody fusion and unilateral pedicle screw fixation.

(a, b) Preoperative anteroposterior and lateral lumbar radiographs. (c, e) Preoperative midsagittal and L4–5 axial T2-weighted magnetic resonance images, respectively, demonstrating L4–5 disc herniation with left lateral recess stenosis. (d, f) Corresponding midsagittal and L4–5 axial T2-weighted magnetic resonance images obtained at the 10-year follow-up. (g, h) Anteroposterior and lateral radiographs obtained 5–7 days after surgery, demonstrating the left-sided unilateral fixation construct. (i, j) Anteroposterior and lateral radiographs obtained at the final follow-up, showing maintained lumbar alignment and maintained positions of the instrumentation and interbody cage.

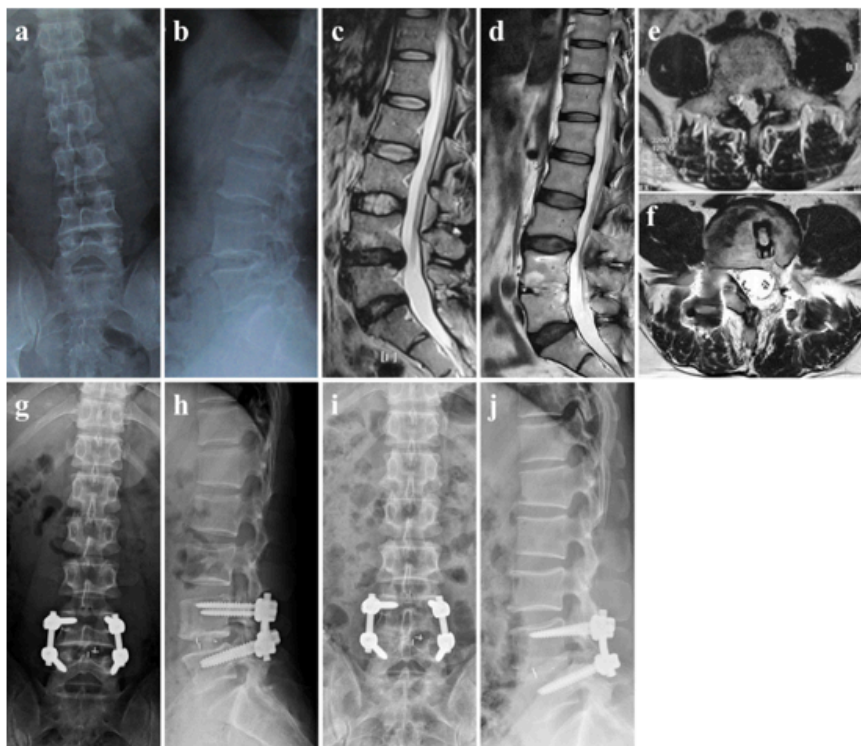


Figure 3

Serial imaging of a representative patient treated with L4–5 transforaminal lumbar interbody fusion and bilateral pedicle screw fixation.

(a, b) Preoperative anteroposterior and lateral lumbar radiographs. (c, e) Preoperative midsagittal and L4–5 axial T2-weighted magnetic resonance images, respectively, showing L4–5 disc herniation with associated neural compression. (d, f) Corresponding midsagittal and L4–5 axial T2-weighted magnetic resonance images obtained at the final follow-up, more than 10 years after surgery. (g, h) Anteroposterior and lateral radiographs obtained 5–7 days after surgery, demonstrating the bilateral fixation construct. (i, j) Anteroposterior and lateral radiographs obtained at the final follow-up, showing preserved lumbar alignment and maintained positions of the instrumentation and interbody cage.