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SUPPLEMENT ARTICLE

Lateral decubitus single position anterior–posterior (AP) fusion shows equivalent results to minimally invasive transforaminal lumbar interbody fusion at one-year follow-up

Kimberly Ashayeri[1] · **J. Alex Thomas**[2] · **Brett Braly**[3] · **Nicholas O'Malley**[4] · **Carlos Leon**[3] · **Ivan Cheng**[5] · **Brian Kwon**[6] · **Mark Medley**[1] · **Leon Eisen**[3] · **Themistocles S. Protopsaltis**[3] · **Aaron J. Buckland**[4]

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Abstract

Purpose This study compares perioperative and 1-year outcomes of lateral decubitus single position circumferential fusion (L-SPS) versus minimally invasive transforaminal lumbar interbody fusion (MIS TLIF) for degenerative pathologies.

Methods Multicenter retrospective chart review of patients undergoing AP fusion with L-SPS or MIS TLIF. Demographics and clinical and radiographic outcomes were compared using independent samples t tests and chi-squared analyses with significance set at $p < 0.05$.

Results A total of 445 patients were included: 353 L-SPS, 92 MIS TLIF. The L-SPS cohort was significantly older with fewer diabetics and more levels fused. The L-SPS cohort had significantly shorter operative time, blood loss, radiation dosage, and length of stay compared to MIS TLIF. 1-year follow-up showed that the L-SPS cohort had higher rates of fusion (97.87% vs. 81.11%; $p = 0.006$) and lower rates of subsidence (6.38% vs. 38.46%; $p < 0.001$) compared with MIS TLIF. There were significantly fewer returns to the OR within 1 year for early mechanical failures with L-SPS (0.0% vs. 5.4%; $p < 0.001$). 1-year radiographic outcomes revealed that the L-SPS cohort had a greater LL (56.6 ± 12.5 vs. 51.1 ± 15.9; $p = 0.004$), smaller PI-LL mismatch (0.2 ± 13.0 vs. 5.5 ± 10.5; $p = 0.004$). There were no significant differences in amount of change in VAS scores between cohorts.

Similar results were seen after propensity-matched analysis and sub-analysis of cases including L5-S1.

Conclusions L-SPS improves perioperative outcomes and does not compromise clinical or radiographic results at 1-year follow-up compared with MIS TLIF. There may be decreased rates of early mechanical failure with L-SPS.

Keywords Single position lumbar fusion · Anterior lumbar interbody fusion (ALIF) · Lateral lumbar interbody fusion (LLIF) · Minimally invasive transforaminal lumbar interbody fusion (MIS TLIF)

Introduction

Single position circumferential (AP) fusion (L-SPS) has been shown to be safe and effective with shorter operative times (OpTime) and decreased estimated blood loss (EBL), length of stay (LOS), and rates of postoperative ileus compared with traditional AP fusion without other differences in complications or radiographic outcomes [1]. It is possible to achieve these improved outcomes while still maintaining the benefits of AP fusion including the ability to place large surface area grafts under the compression of the anterior column and improved biomechanical stability.

Minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) is another MIS technique without requiring repositioning. It allows a familiar, posterior approach,

✉ Kimberly Ashayeri
Kimberly.ashayeri@nyulangone.org

1 Department of Neurosurgery, NYU Langone Medical Center, 462 1st Avenue, Suite 7S4, New York, NY, USA

2 Atlantic Neurosurgical and Spine Specialists, Wilmington, NC, USA

3 Oklahoma Sports, Science and Orthopaedics, Oklahoma City, OK, USA

4 NYU Langone Orthopedic Hospital, New York, NY, USA

5 Austin Spine Surgery, Austin, TX, USA

6 Division of Spine Surgery, New England Baptist Hospital, Boston, MA, USA

minimal muscle dissection and decreased OpTime, EBL, and LOS compared with open TLIF [2]. To date, L-SPS has not been directly compared to MIS TLIF. This study offers a comparison of L-SPS and MIS TLIF perioperative and 1-year outcomes.

Materials and methods

Data collection

This is a multicenter retrospective review comparing patients undergoing primary L-SPS with anterior (ALIF) or lateral lumbar interbody fusion (LLIF) with bilateral percutaneous pedicle screw placement (PPSP) to patients undergoing primary MIS TLIF with bilateral PPSP for degenerative pathologies at 5 institutions from 2013 to 2021. Patients were excluded for age younger than 18 years, previous fusion, unilateral pedicle screws, open decompression, or less than 1-year follow-up. Patient demographics, medical comorbidities, BMI, motor strength exam, procedural characteristics including numbers of levels fused, use of Bone Morphogenic Protein (BMP) or cellular bone matrix (CBM), operative time (OpTime), estimated blood loss (EBL), and radiation dosage (RadDose), and postoperative outcomes were obtained from the electronic medical record. Perioperative outcomes included post-op neurological deficits including hip flexor weakness, ileus, thromboembolic events (Pulmonary Embolus (PE)/Deep Vein Thrombosis (DVT)), surgical site infections (SSI), cardiac, or urinary complications, and returns to the operating room within 90 days. A perioperative complication was considered major if it was Grade III or higher on the Clavien-Dindo classification system [3]. 1-year outcomes included VAS scores, returns to OR for early mechanical failures (EMF), adjacent segment disease (ASD), instrumentation complications, or for neurological deficits. Radiographic analysis included preoperative, postoperative, lumbar lordosis (LL) and pelvic incidence (PI) as well as evidence of fusion or subsidence at 1 year.

Surgical technique

All cases were performed by experienced fellowship-trained orthopedic or neurosurgical spine surgeons. All ALIF cases utilized access surgeons. All L-SPS cases were performed according to previously published techniques [1]. The operating room was set up as depicted in Fig. 1, and patients were positioned as shown in Fig. 2. Briefly, LLIF procedures were performed using the standard lateral transpsoas approach with associated implants and instrumentation (XLIF®, NuVasive, Inc. San Diego, CA). Free-run and triggered EMG monitoring was performed during the approach to map the location of and prevent injury to the lumbar plexus during retractor placement. All ALIF procedures were carried

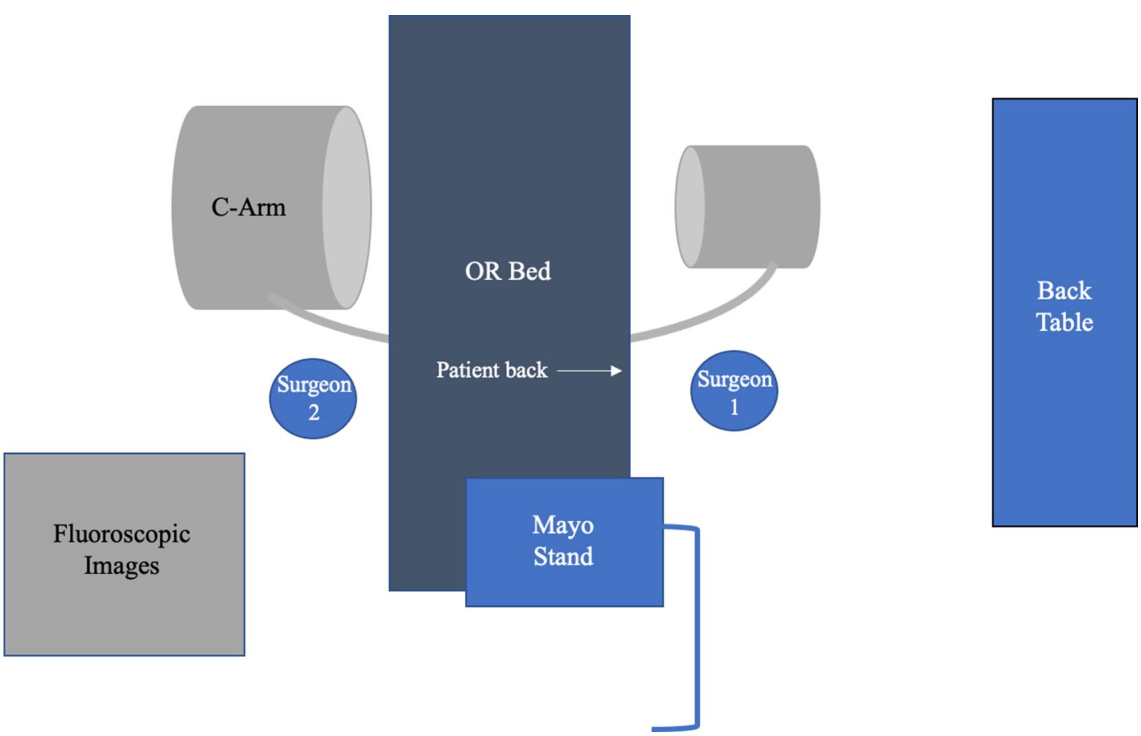

Fig. 1 Operating room setup for lateral decubitus single position circumferential fusion. Diagram depicting the operating room layout for lateral decubitus single position circumferential fusion

Fig. 2 Patient positioning and prepping for lateral decubitus single position circumferential fusion. Left: Anterior view of patient positioning with anatomical locations of the L5 endplate and lateral rectus sheath marked. Right: Posterior view of patient positioning.

out with a vascular access surgeon. An anterior retroperitoneal approach from the lateral decubitus position using a paramidline approach was utilized. Either a buttress plate or integrated locking screws were used to secure to the interbody cage. In all cases, cage dimensions and composition (PEEK vs. Titanium) were chosen per the senior operating surgeon's preference.

PPSF was achieved with the patient maintained in the lateral decubitus position and using either fluoroscopic guidance or computer assisted/robot assistance. Standard technique was utilized for percutaneous pedicle screw placement. Jamshidi needles were placed using a starting point on the junction of the transverse process and lateral facet and advancing with a medialized trajectory to a depth of 25 mm with confirmation that there was no medial pedicle breach. Screw position was confirmed under fluoroscopy, and stimulation with EMG was performed to assess pedicle wall violations.

Statistical analysis

All measures were compared using independent samples t tests and chi-squared analyses as appropriate ($p < 0.05$.) Propensity matching (PSM) was utilized to account for demographic and procedural differences. Analysis was conducted using IBM SPSS Statistics Software (version 21.0, Armonk, NY, USA).

Results

A total of 445 patients were included, 353 undergoing L-SPS and 92 MIS TLIF. The total cohort had an average age of 61.5 ± 11.7 years, were 56.8% female and 43.2% male, and had an average BMI of 30.2 ± 5.9. 17.53% of patients were diabetic, and 8.8% had a history of smoking. The average number of levels fused was 1.4 ± 0.7, 18.4% utilized Bone Morphogenic Protein (BMP), and 53.5% used cellular bone matrix (CBM).

Analysis prior to PSM

A total of 353 patients were included in the L-SPS cohort and 92 patients were included in the MIS TLIF group. The L-SPS versus MIS TLIF cohort had an average age of 62.48 ± 11.5 vs. 57.8 ± 12.1 years, BMI of 29.9 ± 5.5 vs. 30.9 ± 7.1, were 57.5% vs. 64.1% female, 13.9% vs. 31.5% diabetic, and 7.4% vs. 14.1% smokers. Mean number of levels fused in the L-SPS cohort was 1.5 ± 0.7 and 1.2 ± 0.5 in the MIS TLIF cohort. In the L-SPS cohort, 7.9% used BMP and 61.8% used CBM, while the MIS TLIF cohort 58.7% used BMP and 21.7% used CBM. The cohorts showed significant differences in age ($p = 0.001$), diabetes ($p = 0.001$), smoking ($p = 0.041$), number of levels fused ($p < 0.001$), use of BMP ($p < 0.001$), and use of CBM ($p < 0.001$). There were no significant differences in gender or BMI (Table 1).

The L-SPS cohort had significantly shorter OpTime (97.8 ± 53.6 vs. 239.2 ± 76.9 min; $p < 0.001$), lower EBL (88.7 ± 165.2 vs. 214.7 ± 174.3 mL; $p < 0.001$), decreased RadDose (36.5 ± 35.0 vs. 59.0 ± 55.0 mGy; $p = 0.001$), and shorter LOS (1.9 ± 1.7 vs. 3.13 ± 2.1 days; $p < 0.001$) (Table 2).

Analysis of 90-day complications revealed fewer perioperative complications in the L-SPS compared to MIS TLIF group (19.0% vs. 32.6%; $p = 0.005$). L-SPS showed fewer minor complications (9.6% vs. 27.2%; $p < 0.001$), ileus (0.0% vs. 1.1%; $p = 0.050$), and SSI (1.4% vs. 5.4%; $p = 0.021$). There were no differences between the cohorts in major

Table 1 Demographic and procedural characteristics of the total cohort before and after propensity matching (PSM)

	Total cohort (*N* = 445)	Total cohort follow PSM (*N* = 184)
Age (years)	61.5 ± 11.7	57.6 ± 12.2
Gender (%F)	56.9%	59.2%
BMI	30.2 ± 5.9	30.9 ± 6.5
Diabetes (%)	17.5%	28.3%
Smoker (%)	8.8%	12.0%
Levels fused	1.4 ± 0.7	1.2 ± 0.5
Bone morphogenic protein (%)	18.4%	36.4%
Live Cells (%)	53.5%	36.4%

complications (7.7% vs. 5.4%; $p = 0.464$), DVT/PE (1.1% vs. 0.00%; $p = 0.305$), motor deficit (0.4% vs. 1.1%; $p = 0.480$), neuropraxia (8.2% vs. 8.7%; $p = 0.882$), or sensory deficits (9.6% vs. 12.0%; $p = 0.510$). There were no significant differences in returns to OR within 90 days for any reason (6.8% vs. 4.4%; $p = 0.389$), including for hematoma evacuation (0.9% vs. 1.1%; $p = 0.830$), irrigation and debridement (0.6% vs. 0.0%; $p = 0.469$), decompression (1.4% vs. 0.0%; $p = 0.251$), foraminal stenosis (1.4% vs. 1.1%; $p = 0.807$), neurological deficit (1.1% vs. 0.0%; $p = 0.305$), instrumentation revision (3.4% vs. 2.2%; $p = 0.549$), or other reason (0.9% vs. 0.0%; $p = 0.375$) (Table 2).

At 1 year, there were no significant differences in change in VAS scores between the 2 cohorts (− 3.1 ± 2.8 vs − 2.7 ± 3.7; $p = 0.483$). There were significantly fewer returns to OR within 1 year for EMF (0.0% vs. 5.4%;

Table 2 Demographic characteristics and perioperative outcomes in lateral decubitus single position lumbar fusion (L-SPS) versus minimally invasive transforaminal lumbar interbody fusion (MIS TLIF)

	L-SPS (*N* = 353)	MIS TLIF (*N* = 92)	*p* value
Demographics			
Age (years)	62.5 ± 11.5	57.8 ± 12.1	**0.001**
Gender (%F)	57.5%	64.1%	0.586
BMI	30.0 ± 5.5	30.9 ± 7.1	0.172
Diabetes	13.9%	31.5%	**0.001**
Smoker	7.4%	14.1%	**0.041**
Levels fused	1.5 ± 0.7	1.2 ± 0.5	**< 0.001**
Bone morphogenic protein (%)	7.9%	58.7%	**< 0.001**
Live cells (%)	61.8%	21.7%	**< 0.001**
Perioperative outcomes			
Operative time (min)	97.8 ± 53.6	239.2 ± 76.9	**< 0.001**
Estimated blood loss (mL)	88.7 ± 165.2	214.7 ± 174.3	**< 0.001**
Radiation dosage (mGy)	36.5 ± 35.0	59.0 ± 55.0	**0.001**
Length of stay (days)	1.9 ± 1.7	3.1 ± 2.1	**< 0.001**
Intraoperative complications	5.7%	6.5%	0.755
Postoperative complications	19.0%	32.6%	**0.005**
Minor postoperative complication	9.6%	27.2%	**< 0.001**
Major postoperative complication	7.7%	5.4%	0.464
Ileus	0.0%	1.1%	**0.050**
Surgical site infection	1.4%	5.4%	**0.021**
venous Thromboembolism	1.1%	0.0%	0.305
Persistent motor deficit	0.4%	1.1%	0.480
Neuropraxia	8.2%	8.7%	0.882
Sensory deficit	9.6%	12.0%	0.510
Return to OR within 90 days	6.8%	4.4%	0.389
Hematoma evacuation	0.9%	1.1%	0.830
Irrigation and debridement	0.6%	0.0%	0.469
Central decompression	1.4%	0.0%	0.251
Foraminal decompression	1.4%	1.1%	0.807
Neurological deficit	1.1%	0.0%	0.305
Instrumentation revision	3.4%	2.2%	0.549
Other	0.9%	0.00%	0.375

Significant values in bold

$p < 0.001$) with L-SPS. There were no other differences in overall returns to OR within 1 year for any reason (8.7% vs. 12.0%; $p = 0.332$) or for other reasons including returns for ASD (1.1% vs. 3.3%; $p = 0.144$), central (0.9% vs. 0.0%; $p = 0.375$) or foraminal (2.8% vs. 4.4%; $p = 0.458$) stenosis at the operative levels, neurological deficit (0.6% vs. 1.1%; $p = 0.587$), instrumentation revision (3.4% vs. 6.5%; $p = 0.176$), or for other reason including postoperative compressive collection or infection (1.7% vs. 2.2%; $p = 0.760$) (Table 3).

Radiographic analysis revealed that at 1-year follow-up, the L-SPS cohort showed higher rates of fusion compared with the MIS TLIF cohort (97.87% vs. 81.11%; $p = 0.006$). There were significantly higher rates of subsidence (6.38% vs. 38.46%; $p < 0.001$) in the MIS TLIF cohort compared to L-SPS, as illustrated in Fig. 3. There were no significant differences in baseline alignment between L-SPS and MIS TLIF cohorts including PI (56.7 ± 10.5 vs. 58.1 ± 11.3; $p = 0.314$), baseline LL (52.6 ± 11.3 vs. 54.0 ± 12.1; $p = 0.408$), and PI-LL mismatch (4.1 ± 10.1 vs. 5.4 ± 12.0; $p = 0.430$). 90-day radiographic outcomes revealed that the L-SPS cohort had a greater post-op LL (56.3 ± 11.18 vs. 52.0 ± 10.8; $p = 0.002$) and smaller post-op PI-LL mismatch (0.5 ± 9.9 vs. 5.8 ± 10.8; $p < 0.001$). 1-year radiographic outcomes revealed that the L-SPS cohort had a greater LL (56.6 ± 12.5 vs. 51.1 ± 15.9; $p = 0.004$), smaller PI-LL mismatch (0.2 ± 13.0 vs. 5.5 ± 10.5; $p = 0.004$). The L-SPS cohort also exhibited greater improvement in LL from

Table 3 1-year outcomes in lateral decubitus single position lumbar fusion (L-SPS) versus minimally invasive transforaminal lumbar interbody fusion (MIS TLIF)

	L-SPS (*N* = 353)	MIS TLIF (*N* = 92)	*p* value
1-year clinical outcomes			
ΔVAS score	− 3.1 ± 2.8	− 2.7 ± 3.7	0.483
Return to OR within 1 year	8.7%	12.0%	0.332
Early mechanical failure	0.0%	5.4%	**< 0.001**
Adjacent segment disease	1.1%	3.3%	0.144
Central stenosis	0.9%	0.0%	0.375
Foraminal stenosis	2.8%	4.4%	0.458
Neurological deficit	0.6%	1.1%	0.587
Instrumentation revision	3.4%	6.5%	0.176
Other	1.7%	2.2%	0.760

Significant values in bold

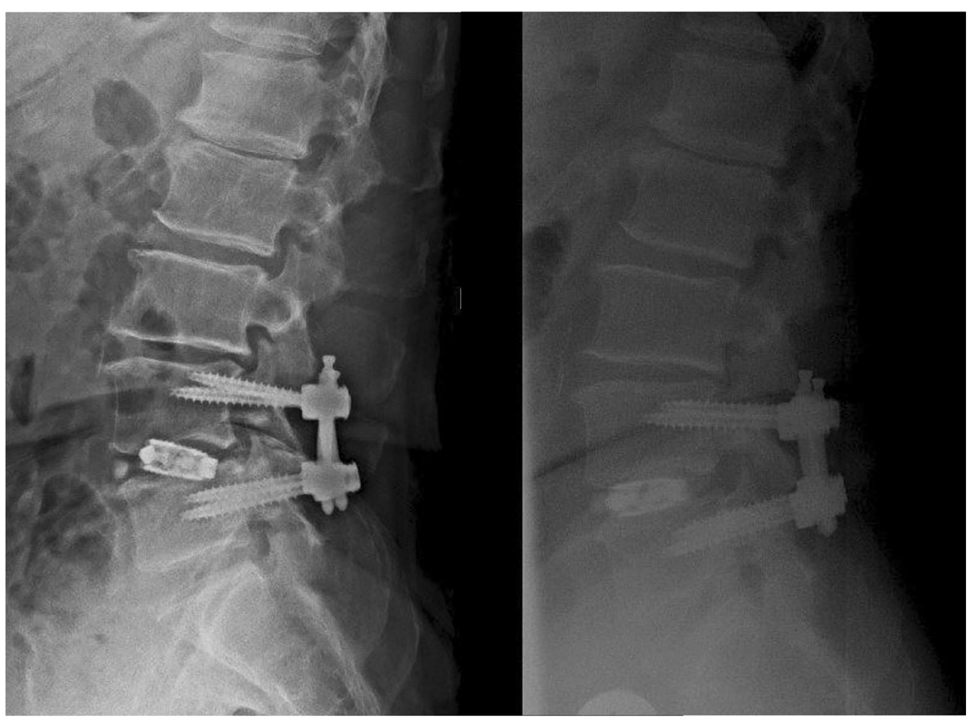

Fig. 3 Example case of subsidence in MIS TLIF patient. Comparison of 1-year postoperative (left) and first postoperative (right) sagittal XRs in patient who underwent single-level L4-5 minimally invasive transforaminal lumbar interbody fusion (MIS TLIF)

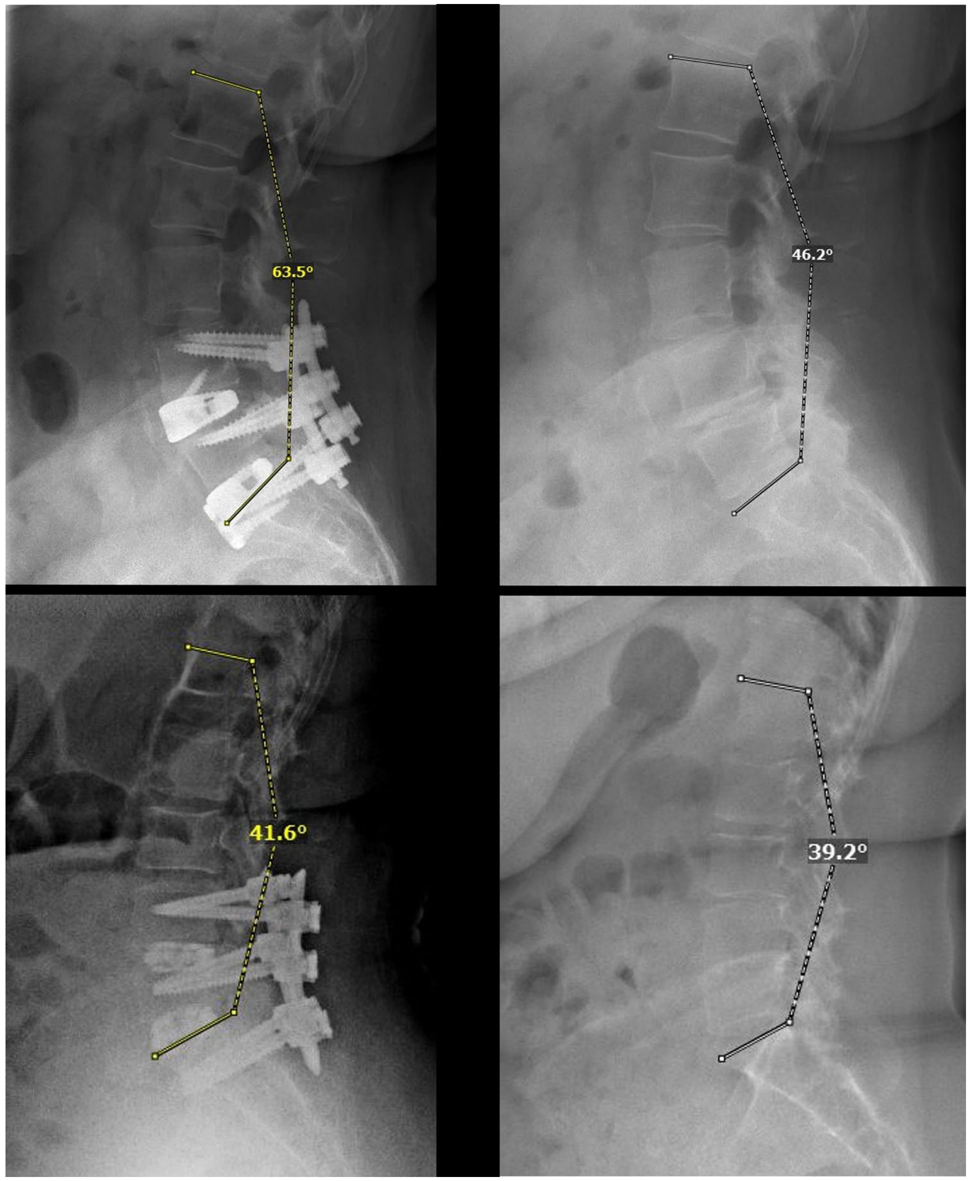

Fig. 4 Example cases comparing change in alignment in two-level SPS versus MIS TLIF. Top images: Postoperative (left) compared to preoperative (right) sagittal XRs of patient undergoing two-level single position circumferential fusion (L-SPS) with anterior lumber interbody fusion with 17.3 degree increases in lumbar lordosis. Bottom Images: Postoperative (left) compared to preoperative (right) sagittal XRs of patient undergoing two-level minimally invasive transforaminal lumbar interbody fusion (MIS TLIF) with 2.4 degree increases in lumbar lordosis

baseline to 1 year (3.2 ± 8.8 vs. − 3.4 ± 13.5; $p < 0.001$) and in PI-LL (− 3.1 ± 10.7 vs. 1.3 ± 8.0; $p = 0.006$), as illustrated in Fig. 4. There were no significant differences in change in LL from post-op to 1 year − 0.2 ± 9.3 vs. − 1.6 ± 13.3; $p = 0.343$) or in change in PI-LL mismatch from post-op to 1 year (0.7 ± 8.6 vs. 0.1 ± 5.0; $p = 0.547$) (Table 4).

Analysis following PSM

Following PSM for age, diabetes, smoking, and number of levels fused, 184 patients remained (92 L-SPS and 92 MIS TLIF). The total cohort had an average age of 57.6 ± 12.2 years, was 59.2% female, and had an average BMI of 30.9 ± 6.5. 28.3% were diabetic and 12.0% were smokers. The average number of levels fused was 1.2 ± 0.5, 36.4% used BMP, and 36.4% used CBM. Following propensity matching there were no significant differences in demographics. There was significantly greater usage of BMP in the MIS TLIF cohort (14.1% vs. 58.7%; $p < 0.001$) and significantly more live cell usage in the L-SPS cohort (51.1% vs. 21.7%; $p < 0.001$) (Table 1). The findings after PSM continued to show shorter OpTime and decreased perioperative EBL, LOS, RadDose, and overall complication rates (Table 5). Additionally, a difference in returns to OR within 1 year for mechanical failures (0.0% vs. 5.4%; $p = 0.023$) was still observed. There were no significant differences in VAS scores or overall returns to OR within 1 year for any other reason (Table 6). Radiographic analysis revealed no differences in baseline alignment between the cohorts but the L-SPS had a greater post-op LL and smaller PI-LL mismatch at 90 days and at 1 year. There were no significant

Table 4 Radiographic outcomes in lateral decubitus single position lumbar fusion (L-SPS) versus minimally invasive transforaminal lumbar interbody fusion (MIS TLIF)

	L-SPS (N = 353)	MIS TLIF (N = 92)	p value
Radiographic outcomes			
Evidence of fusion	97.9%	81.1%	**< 0.001**
Subsidence	12.1%	38.5%	**< 0.001**
Baseline LL	52.6 ± 11.3	54.0 ± 12.1	0.408
PI	56.7 ± 10.5	58.1 ± 11.3	0.314
Baseline PI-LL mismatch	4.1 ± 10.1	5.4 ± 12.0	0.430
Post-op LL	56.3 ± 11.2	52.0 ± 10.8	**0.002**
Post-op PI-LL mismatch	0.5 ± 9.9	5.8 ± 10.8	**< 0.001**
1-Year LL	56.6 ± 12.5	51.1 ± 15.9	**0.004**
1-Year PI-LL mismatch	0.2 ± 13.0	5.5 ± 10.5	**0.004**
ΔLL baseline to 1 year	3.2 ± 8.8	− 3.4 ± 13.5	**< 0.001**
ΔPI-LL baseline to 1 year	− 3.1 ± 10.7	1.3 ± 8.0	**0.006**
ΔLL post-op to 1 year	− 0.2 ± 9.3	− 1.6 ± 13.3	0.343
ΔPI-LL post-op to 1 year	0.7 ± 8.6	0.1 ± 5.0	0.547

Significant values in bold

differences between L-SPS and MIS TLIF in change in LL or in PI-LL mismatch from post-op to 1 year (Table 7).

Sub-analysis of L5-S1 surgeries

L5-S1 surgeries were analyzed separately, which included 136 L-SPS and 41 MIS TLIF cases. The L-SPS group was older (59.0 ± 12.7 vs. 53.5 ± 12.1, $p = 0.016$), had more levels fused (1.7 ± 0.8 vs. 1.3 ± 0.5, $p < 0.001$), and lower use of BMP (8.8% vs. 68.3%, $p < 0.001$) than the MIS TLIF cohort. L5-S1 L-SPS showed shorter OpTime (235.9 ± 76.1 vs. 125.3 ± 53.0 min, $p < 0.001$), and decreased EBL (200.4 ± 160.1 vs. 136.9 ± 248.0 mL, $p < 0.001$), LOS (3.1 ± 2.2 vs. 2.1 ± 1.3 days, $p = 0.007$), rates of durotomy (0.0% vs. 4.9%; $p = 0.010$), and rate of minor postoperative complications (14.7% vs. 31.7%, $p = 0.014$) compared to the MIS TLIF cohort. The L-SPS cohort had a 4.8% rate of sensory deficit compared to 14.6% in the MIS TLIF cohort ($p = 0.056$) (Table 8).

There was a significantly higher fusion rate (100.0% vs. 76.9%; $p < 0.001$), lower subsidence rate (9.5% vs. 29.3%; 0.008), and lower EMF rate (0.0% vs. 4.9%, $p = 0.010$) in L-SPS patients. Improvement in LL (+ 5.0 ± 8.1 vs. − 2.5 ± 5.3; $p < 0.001$) and in PI-LL mismatch (− 4.5 ± 8.5 vs. + 1.2 ± 5.5; $p = 0.020$) at 1 year compared to baseline was greater in the L-SPS compared to MIS TLIF cohort (Table 9).

Discussion

L-SPS is a novel MIS technique for circumferential fusion with improved perioperative and 1-year outcomes compared with AP fusion with patient repositioning. Both L-SPS and MIS TLIF are muscle-sparing interbody techniques that do not require repositioning the patient. Traditionally, surgeons may opt to use MIS TLIF techniques due to OpTime, EBL, LOS, and complication profile of AP fusion [4]. However, this study found equivalent or improved perioperative outcomes with L-SPS compared to MIS TLIF. After PSM for demographic and procedural characteristics, L-SPS continued to demonstrate improved OpTime, EBL, RadDose, and LOS.

The OpTime, EBL, RadDose, and LOS demonstrated in prior MIS TLIF studies were similar [5–10]. Additionally, the current study found fewer postoperative complications in the L-SPS cohort compared to MIS TLIF. This was largely driven by minor complications, as there were no significant differences in major complications. There were also fewer sensory deficits following L-SPS compared with MIS TLIF. Numerous studies have demonstrated increased OpTime, EBL, LOS, and complications with AP fusion compared with TLIF [11–14]. A prior comparison of MIS TLIF and AP fusion showed that AP fusion was associated with a twofold higher complication rate, EBL, OpTime and LOS [11]. In a comparison of open or MIS TLIF versus ALIF utilizing the National Surgical Quality Improvement Project (NSQIP) Database, Upadhyayula et al. found that ALIF cohorts had increased pulmonary complications and hospital stays [12]. Phan et al.'s meta-analysis of TLIF versus ALIF also found that ALIF was associated with longer hospitalization with similar complication rates [15]. This first direct comparison of L-SPS with ALIF and/or LLIF versus MIS TLIF reveals that circumferential fusion can be accomplished more efficiently than MIS TLIF with less radiation and fewer complications.

Of note, MIS TLIF showed lower rates of fusion and more returns to OR for EMF at 1-year follow-up compared

Table 5 Demographic characteristics and perioperative outcomes in lateral decubitus single position lumbar fusion (L-SPS) versus minimally invasive transforaminal lumbar interbody fusion (MIS TLIF) following propensity matching (PSM)

	L-SPS PSM* (*N* = 92)	MIS TLIF PSM* (*N* = 92)	*p* value
Demographics			
Age (years)	57.4 ± 12.7	57.8 ± 12.1	0.812
Gender (%F)	54.4%	64.1%	0.177
BMI	31.4 ± 5.9	30.9 ± 7.1	0.621
Diabetes	25%	32%	0.326
Smoker	9.8%	14.1%	0.363
Levels fused	1.2 ± 0.4	1.2 ± 0.4	0.274
Bone morphogenic protein (%)	14.1%	58.7%	**< 0.001**
Live cells (%)	51.1%	21.7%	**< 0.001**
Perioperative outcomes			
Operative time (min)	98.8 ± 57.9	239.2 ± 76.9	**< 0.001**
Estimated blood loss (mL)	80.1 ± 84.6	214.7 ± 174.3	**< 0.001**
Radiation dosage (mGy)	39.8 ± 34.5	59.0 ± 55.0	**0.019**
Length of stay (days)	1.8 ± 1.1	3.1 ± 2.1	**< 0.001**
Intraoperative complications	4.4%	6.5%	0.515
Postoperative complications	17.4%	32.6%	**0.017**
Minor postoperative complication	7.6%	27.2%	**< 0.001**
Major postoperative complication	7.6%	5.4%	0.550
Ileus	0.0%	1.1%	0.316
Surgical site infection	2.2%	5.4%	0.248
Venous thromboembolism	0.0%	0.0%	1.000
Persistent motor deficit	0.0%	1.1%	0.451
Neuropraxia	7.6%	8.7%	0.788
Sensory deficit	0.0%	12.0%	**< 0.001**
Return to OR within 90 days	5.4%	4.4%	0.733
Hematoma evacuation	0.0%	1.1%	0.316
Irrigation and debridement	1.1%	0.0%	0.316
Central decompression	2.2%	0.0%	0.155
Foraminal decompression	1.1%	1.1%	1.000
Neurological deficit	2.2%	0.0%	0.155
Instrumentation revision	3.3%	2.2%	0.650
Other	1.1%	0.0%	0.316

Significant values in bold

*Propensity matched by age, smoker, diabetes, levels fused

to L-SPS. While there is limited literature comparing EMF and pseudoarthrosis between AP fusion and MIS TLIF, the rates are comparable to those seen in prior studies. Analyses of 1- and 2-level MIS TLIFs with a minimum of 1-year follow-up have shown fusion rates of 81–92% [16–18]. In a prospective randomized trial, Serban et al. found a fusion rate of 90% among an MIS TLIF cohort at 1-year follow-up [19]. Studies of short segment fusion with ALIF have consistently shown rates of 93.5–100% [20, 21]. In a study of AP fusion with LLIF, Strom et al. found a fusion rate of 94% with percutaneous pedicle screw placement [22]. Therefore, the finding of higher rates of fusion among the L-SPS cohort is consistent with previous literature on MIS TLIF and traditional AP fusion. Additionally, while BMP has been associated with higher rates of fusion, the L-SPS cohort had higher rates of fusion than the MIS TLIF despite lower usage of BMP [23].

MIS TLIF was demonstrated to have significantly higher rates of subsidence when compared to L-SPS at 1 year. These rates of subsidence are similar to those previously reported in literature on MIS TLIF, ALIF, and LLIF. The Yao et al. study of 126 MIS TLIFs with 2-year follow-up found a similar rate of subsidence of 34.1% [24]. In Pisano et al.'s analysis of 89 patients with a minimum of 1-year follow-up, a subsidence rate of 50.6% [25]. In contrast to TLIF, prior studies have shown that subsidence rates in ALIF and XLIF are lower than reported rates in MIS TLIF. In a comparison of open TLIF and ALIF, cage subsidence rates at

Table 6 1-year outcomes in lateral decubitus single position lumbar fusion (L-SPS) versus minimally invasive transforaminal lumbar interbody fusion (MIS TLIF) following propensity matching (PSM)

	L-SPS PSM* ($N=92$)	MIS TLIF PSM* ($N=92$)	p value
1-year clinical outcomes			
Return to OR within 1 year	7.8%	12.0%	0.345
Early mechanical failure	0.0%	5.4%	**0.023**
Adjacent segment disease	2.2%	3.3%	0.650
Central stenosis	0.0%	0.0%	1.000
Foraminal stenosis	2.2%	4.4%	0.406
Neurological deficit	0.0%	1.1%	0.316
Instrumentation revision	2.2%	6.5%	0.148
Other	0.0%	2.2%	0.155
ΔVAS score	-3.3 ± 2.2	-2.7 ± 3.7	0.239

Significant values in bold

*Propensity matched by age, smoker, diabetes, levels fused

1-year were found to be 7.7% in the ALIF cohort and 33.3% in the TLIF cohort [26]. In Rao et al.'s study of 147 patients with 18-month follow-up, the authors found a 10.2% subsidence rate. Tempel et al.'s analysis of 297 patients undergoing LLIF found a similar rate of 11.4% [27]. Therefore, it is not surprising that in the current study, L-SPS with ALIF and/or XLIF demonstrated lower rates of subsidence [26].

Furthermore, superior radiographic outcomes were observed in the L-SPS group. The postoperative LL was greater in the L-SPS cohort compared to MIS TLIF. In prior radiographic comparisons of ALIF/LLIF versus TLIF, Ahlquist et al. found that ALIF and LLIF produced greater improvements in radiographic measurements postoperatively compared with TLIF, with ALIF showing a change in LL of 5.5 degrees, LLIF of 7.7 degrees, and TLIF 2.7 degrees ($p < 0.050$) [28]. These results proved to be durable over time, as the change in LL from pre-op to 1 year greater in L-SPS group compared with the MIS TLIF cohort (3.73 ± 8.33 vs. -3.41 ± 13.50; $p = 0.001$) and particularly notable in the L5-S1 sub-analysis which showed a change in LL to be 5.0 ± 8.1 vs. -2.5 ± 5.3; $p < 0.001$. While circumferential fusion with L-SPS technique increased LL at 1 year, the MIS TLIF group experienced kyphosis. This is consistent with past literature showing that AP fusion with ALIF or LLIF serves to provide more powerful lordosis than TLIF procedures [29–31].

As a retrospective study, it is open to selection bias. PSM was undertaken to account for differences in demographics and procedural characteristics. Additionally, as a multicenter study, it is not possible to account for small differences in patient selection and surgical technique between institutions. However, all surgeons contributing cases are experienced,

Table 7 Radiographic outcomes in lateral decubitus single position lumbar fusion (L-SPS) versus minimally invasive transforaminal lumbar interbody fusion (MIS TLIF) following propensity matching (PSM)

	L-SPS PSM* ($N=92$)	MIS TLIF PSM* ($N=92$)	p value
Radiographic outcomes			
Evidence of fusion	97.9%	81.1%	**0.006**
Subsidence	6.4%	38.5%	**< 0.001**
Baseline LL	55.2 ± 10.2	54.0 ± 12.1	0.400
PI	58.5 ± 11.2	58.1 ± 11.3	0.821
Baseline PI-LL mismatch	3.3 ± 11.5	5.4 ± 12.0	0.349
Post-op LL	59.2 ± 11.5	52.0 ± 10.8	**< 0.001**
Post-op PI-LL mismatch	-0.2 ± 11.4	5.8 ± 10.8	**0.001**
1-Year LL	58.8 ± 11.1	51.1 ± 15.9	**0.004**
1-Year PI-LL mismatch	-1.2 ± 12.8	5.5 ± 10.5	**0.003**
ΔLL baseline to 1 year	3.7 ± 8.3	-3.4 ± 13.5	**0.001**
ΔPI-LL baseline to 1 year	-3.5 ± 9.0	1.3 ± 8.0	**0.011**
ΔLL Post-op to 1 year	-0.3 ± 9.2	-1.6 ± 13.3	0.554
ΔPI-LL post-op to 1 year	1.0 ± 8.5	0.1 ± 5.0	0.469

Significant values in bold

*Propensity matched by age, smoker, diabetes, levels fused

Table 8 Demographic, procedural, and perioperative outcomes in lateral decubitus single position lumbar fusion (L-SPS) versus minimally invasive transforaminal lumbar interbody fusion (MIS TLIF) at L5-S1

	L5-S1 L-SPS (N=136)	L5-S1 MIS TLIF (N=41)	p value
Demographics			
Age (years)	59.0 ± 12.7	53.5 ± 12.1	**0.016**
Gender (%F)	56.6%	48.8%	0.377
BMI	29.9 ± 4.9	31.1 ± 7.0	0.235
Diabetes	15.4%	26.8%	0.097
Smoker	8.1%	14.6%	0.212
Levels fused	1.7 ± 0.8	1.3 ± 0.5	**< 0.001**
Bone morphogenic protein (%)	8.8%	68.3%	**< 0.001**
Live cells (%)	39.7%	51.2%	0.191
Perioperative outcomes			
Operative time (min)	125.3 ± 53.0	235.9 ± 76.1	**< 0.001**
Estimated blood loss (mL)	136.9 ± 248.0	200.4 ± 160.1	**< 0.001**
Radiation dosage (mGy)	44.7 ± 42.8	63.2 ± 61.7	0.115
Length of stay (days)	2.1 ± 1.3	3.1 ± 2.2	**0.007**
Intraoperative complications	7.4%	9.8%	0.617
Durotomy	0.0%	4.9%	**0.010**
posteroperative complications	25.0%	39.0%	0.080
Minor postoperative complication	14.7%	31.7%	**0.014**
Major postoperative complication	10.3%	7.3%	0.571
Ileus	0.0%	0.0%	1.000
Surgical site infection	3.0%	7.3%	0.208
Venous thromboembolism	2.9%	0.0%	0.862
Persistent motor deficit	1.2%	0.0%	0.483
Neuropraxia	6.0%	7.3%	0.770
Sensory deficit	4.8%	14.6%	*0.056*
Return to OR within 90 days	9.6%	7.3%	0.661
Hematoma evacuation	0.0%	0.0%	1.000
Irrigation and debridement	1.5%	0.0%	0.435
Central decompression	0.7%	0.0%	0.582
Foraminal decompression	2.2%	2.4%	0.930
Neurological deficit	2.21%	0.00%	0.337
Instrumentation revision	5.1%	4.9%	0.945
Other	1.5%	0.0%	0.435

Significant values in bold

MIS surgeons, and therefore, there are unlikely to be clinically significant differences in outcomes.

The study is also limited by lack of longer-term follow-up to evaluation for pseudoarthrosis, other mechanical failures, and the differences in spinopelvic mismatch. However, it is important to recognize that there are not early failures with this novel technique. Additionally, positive 1-year clinical outcomes in lumbar spine surgery have been shown to have predictive value of longer-term outcomes [32].

Conclusion

Circumferential fusion with ALIF and/or LLIF and PPSF has clear advantages over MIS TLIF: high rates of fusion, less subsidence, and improved postoperative sagittal alignment. In the past, AP fusion required long surgeries with repositioning, high blood loss, and a unique complication profile including greater rates of postoperative ileus than in posterior fusion. This study shows that L-SPS improves operative efficiency and outcomes and low rates

Table 9 1-year and radiographic outcomes in lateral decubitus single position lumbar fusion (L-SPS) versus minimally invasive transforaminal lumbar interbody fusion (MIS TLIF) at L5-S1

	L5-S1 L-SPS (*N* = 136)	L5-S1 MIS TLIF (*N* = 41)	*p* value
Radiographic outcomes			
Evidence of fusion	100.0%	76.9%	**< 0.001**
Subsidence	9.5%	29.3%	**0.008**
Baseline LL	52.6 ± 12.9	52.7 ± 11.2	0.977
PI	55.5 ± 11.5	54.9. ± 10.8	0.784
Baseline PI-LL mismatch	2.7 ± 10.4	1.2 ± 11.5	0.589
Post-op LL	57.7 ± 12.5	51.3 ± 9.9	**0.005**
Post-op PI-LL mismatch	− 2.1 ± 9.5	3.5 ± 9.7	**0.004**
1-year LL	58.4 ± 11.0	53.0 ± 9.6	**0.017**
1-year PI-LL mismatch	− 3.0 ± 9.9	2.4 ± 8.2	**0.011**
ΔLL baseline to 1 year	5.0 ± 8.1	− 2.5 ± 5.3	**< 0.001**
ΔPI-LL baseline to 1 year	− 4.5 ± 8.5	1.2 ± 5.5	**0.020**
ΔLL post-op to 1 year	0.5 ± 9.7	0.0 ± 3.7	0.799
ΔPI-LL post-op to 1 year	0.5 ± 7.0	0.1 ± 3.7	0.764
Returns to OR within 1 year			
Return to OR within 1 year	9.6%	14.6%	0.374
Early mechanical failure	0.0%	4.9%	**0.010**
Adjacent segment disease	0.7%	4.9%	0.072
Central stenosis	0.0%	0.0%	1.000
Foraminal stenosis	3.7%	7.3%	0.325
Neurological deficit	0.7%	2.4%	0.366
Instrumentation revision	4.4%	9.8%	0.194
Other	2.2%	2.4%	0.930
VAS			
ΔVAS Score	− 3.6 ± 2.2	− 2.7 ± 4.3	0.597

Significant values in bold

of complications, while still maintaining the benefits of traditional AP fusion over MIS TLIF both perioperatively and at 1 year. This makes L-SPS an attractive alternative to MIS TLIF for the treatment of degenerative pathologies.

Availability of data and material Available.

Declarations

Conflicts of interest J. Alex Thomas is a consultant for Nuvasive. Brett Braly is a consultant for Stryker and Nuvasive. Ivan Cheng is a consultant for Nuvasive and Globus Medical. Brian Kwon is a consultant for Nuvasive. Themistocles S. Protopsaltis is a consultant for Altus Partners, Globus Medical, Nuvasive, and Zimmer Biomet. Aaron J. Buckland is a consultant for Nuvasive, Biedermann Motech, Medtronic, Evolution Spine, Altus Partners, and Zimmer Biomet.

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