



Single position L5-S1 lateral ALIF with simultaneous robotic posterior fixation is safe and improves regional alignment and lordosis distribution index

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Abstract

Purpose Minimally invasive single position lateral ALIF at L5-S1 with simultaneous robot-assisted posterior fixation has technical and anatomic considerations that need further description.

Methods This is a retrospective case series of single position lateral ALIF at L5-S1 with robotic assisted fixation. End points included radiographic parameters, lordosis distribution index (LDI), complications, pedicle screw accuracy, and inpatient metrics.

Results There were 17 patients with mean age of 60.5 years. Eight patients underwent interbody fusion at L5-S1, five patients at L4-S1, two patients at L3-S1, and one patient at L2-S1 in single lateral position. Operative times for 1-level and 2-level cases were 193 min and 278 min, respectively. Mean EBL was 71 cc. Mean improvements in L5-S1 segmental lordosis were $11.7 \pm 4.0^\circ$, L1-S1 lordosis of $4.8 \pm 6.4^\circ$, sagittal vertical axis of -0.1 ± 1.7 cm°, pelvic tilt of $-3.1 \pm 5.9^\circ$, and pelvic incidence lumbar–lordosis mismatch of $-4.6 \pm 6.4^\circ$. Six patients corrected into a normal LDI (50–80%) and no patients became imbalanced over a mean follow-up period of 14.4 months. Of 100 screws placed in lateral position with robotic assistance, there were three total breaches (two lateral grade 3, one medial grade 2) for a screw accuracy of 97.0%. There were no neurologic, vascular, bowel, or ureteral injuries, and no implant failure or reoperation.

Conclusion Single position lateral ALIF at L5-S1 with simultaneous robotic placement of pedicle screws by a second surgeon is a safe and effective technique that improves global alignment and lordosis distribution index.

Keywords Oblique lumbar interbody fusion (OLIF) · Anterior lumbar interbody fusion (ALIF) · Lateral surgery · L5-S1 · Mazor X Stealth Edition · Spinal robotics · Minimally invasive surgery · Single position surgery · Lordosis distribution index

Introduction

Lumbar interbody fusion is a common surgical intervention to stabilize painful vertebral segments, correct spinal deformities, restore lumbar lordosis, and decompress the spinal nerves [1]. Oblique lumbar interbody fusion (OLIF)

is one such iteration of this technique which has shown to be feasible and promising [2]. A unique advantage of OLIF is the opportunity for single position surgery (SPS) with simultaneous interbody fusion and posterior fixation via a two surgeon technique [3]. A multicentre comparison of single-position versus dual-position surgery, which involves “flipping” the patient, showed that SPS has advantages of lower operative time, blood loss, fluoroscopic radiation, shorter hospital stay, and lower incidence of post-operative ileus [4]. Various approaches in lumbar interbody fusion often employ intraoperative navigation or robotics platforms to improve pedicle screw accuracy. When compared to contemporary navigation, spinal robotics have shown to improve screw accuracy, lower fluoroscopic radiation, and preserve operative time efficiency [5, 6]. Spinal robotics in combination with OLIF streamlines this opportunity for a two-surgeon

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workflow, which has been termed simultaneous robotic single position surgery (SR-SPS). OLIF at L5-S1, which is also described as lateral ALIF utilizes a minimally invasive oblique retroperitoneal corridor to expose the anterior midline of the disc space.

The lordosis distribution index (LDI) illustrates how the proportion of lordosis at L4-S1, when compared to total lordosis of L1-S1, remains a key target of healthy lordosis especially in terms of segmental alignment, global alignment, overall sagittal balance, and a reduction in the risk of adjacent segment disease and proximal junctional failure [7]. Distribution of the majority of lumbar lordosis in the lower L4-S1 arc of the spine is a significant consideration for a well-balanced spine. Although anterior lumbar interbody fusion (ALIF) is the strongest interbody technique to accomplish this, the bifurcation of the aorta and inferior vena cava into the common iliac vessels bring these structures into the operative corridor and increase the risk of vascular injuries among other potential complications [8].

Given the importance of the L5-S1 level for lordosis restoration as it relates to overall balance, and the benefits of SR-SPS with robotic systems, we report our institution's experience performing single position surgery with lateral ALIF at L5-S1 and simultaneous robot-assisted posterior fixation with a second surgeon.

Methods

This is a retrospective single centre series of 17 consecutive cases of SR-SPS including the L5-S1 level performed in lateral decubitus by a single attending surgeon (senior author M.H.P.) with a resident surgeon assistant from July 2020 to August 2022. Inclusion criteria were patients undergoing L5-S1 interbody fusion via the lateral decubitus ALIF approach with pedicle screws placed in the same position with robotic assistance. Exclusion criteria included patients with only unilateral pedicle screw fixation, prior implants at L5-S1 requiring revision, or requiring prone repositioning for posterior fixation. This research was approved by the Institutional Review Board of University of California San Diego, and all patients consented to research involvement prior to enrolment. End points included radiographic alignment parameters including LDI, major and minor complications, pedicle screw accuracy, and inpatient stay metrics. Measurements were taken on a PACS station with a suite of measurement tools. Statistical analyses were conducted in Stata (17, StataCorp LLC, College Station, TX). A student's *t* test or Wilcoxon rank sum was used for the comparison of means. Initial post-operative X-rays were performed as standing AP/lateral lumbar X-rays during their inpatient stay and this served as comparison controls for later standing X-rays at follow-up. Major complications were defined

as (1) any neurologic, vascular, bowel, or ureteral injury; (2) return to OR for any reason; or (3) implant failure. All other adverse events were defined as minor complications. LDI was defined as normal (LDI 50–80%), hypolordotic (LDI < 50%), or hyperlordotic (LDI > 80%). The Gertzbein and Robbins classification was used to grade malposition of pedicle screws as previously described [9].

SR-SPS technique

This technique represents a two surgeon near-simultaneous workflow including a posterior (pedicle screw) surgeon and an anterior (lateral ALIF) surgeon (Fig. 1) [3, 10]. All patients undergo a preoperative CT (computed tomography) scan which is used to plan pedicle screw placement, and this plan is registered to the patient with two intraoperative fluoroscopy X-rays. We typically use intraoperative CT to register only if patients are travelling a great distance and are unable to obtain preoperative CT scans, and for implant confirmation.

The patient is positioned in right lateral decubitus with the left side facing up, and the left leg is extended to accommodate the sacral slope. A generous amount of taping is used to secure the patient to the operating room table to minimize movement and maximize robotic precision. Muscle relaxants are also given at the start of the case to facilitate anterior exposure and decrease the occurrence of any sag or movement that may interfere with accuracy after the patient has been registered to the robotics platform.

Posterior surgeon

The robotic arm (Medtronic Mazor X Stealth Edition, Minnesota, MN) is sent to the posterior screw trajectories and pedicle screws are placed percutaneously using robotic assistance (Fig. 2). This occurs while the anterior surgeon creates an exposure to the disc space. We place the right-sided “down” side screws first proximal to distal, then repeat with the left-sided “up” side screws. If S2-alar-iliac screws are planned, they are placed last. Once all screws are placed, the posterior surgeon may need to pause while the anterior surgeon finishes exposure of the L5-S1 disc space if not already completed. The discectomy is performed, and the cage is placed, followed by an intraoperative CT confirmation spin. Once finished, the posterior surgeon then places rods and set screws and closure proceeds in the usual fashion.

Anterior surgeon

The robot navigation is used to mark the L5-S1 level on the skin for incision planning and a retroperitoneal exposure is performed down to the anterior L5-S1 disc space. Care is taken not to move the patient during this exposure while the

Fig. 1 Intraoperative set-up showing a two-surgeon technique whereby an anterior surgeon can expose down to L5-S1 while the posterior surgeon places pedicle screws with robotic assistance

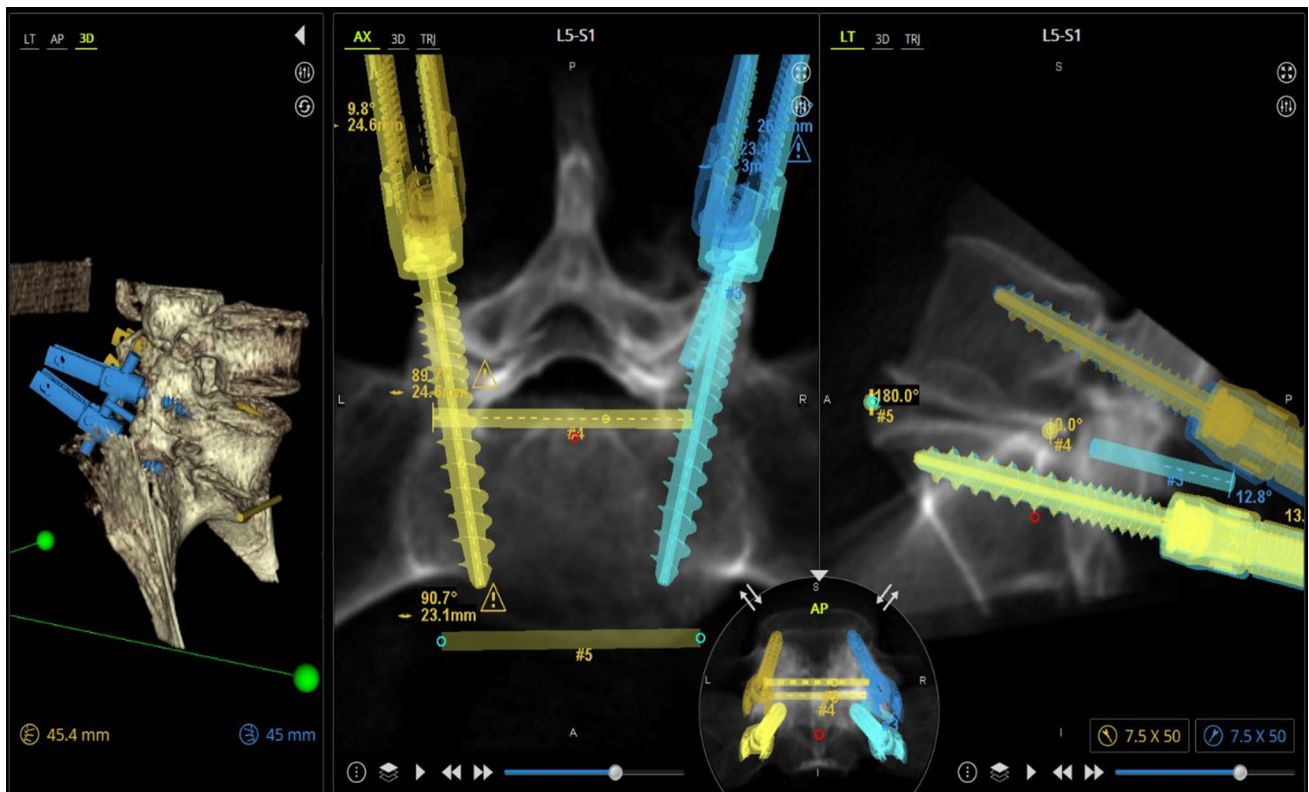


Fig. 2 Robotic software plan showing L5 and S1 screws as well as the anterior and posterior border of the L5-S1 disc which can be targeted with the robotics platform for localization

posterior surgeon is simultaneously placing all percutaneous pedicle screws with registered robotic assistance. Once the disc spaced is exposed between the bifurcation of the great vessels, the anterior surgeon pauses until all posterior screws are placed. The anterior surgeon then proceeds with the discectomy and cage placement followed by an intraoperative CT confirmation spin (Fig. 3). Closure then proceeds in the usual fashion while the posterior surgeon begins rod placement.

Results

Baseline characteristics and review of treatment results are shown in Tables 1 and 2, respectively. A total of 17 patients (10 male) whose mean age was 60.8 years (range 30–80) underwent SR-SPS including lateral ALIF at L5-S1 over a 2-year period. Mean BMI was 29.5 ± 5.5 kg/m² (range 20.4–39.9). Average clinical follow-up was 14.4 months (range 4.3–33.9 months) and radiographic follow-up was 13.4 months (range 2.7–28.3). The treating diagnosis was degenerative disc disease in 15 patients causing back pain, neurogenic claudication, and/or lumbar radiculopathy, while two patients presented with a deformity diagnosis of sagittal imbalance. There were eight patients who underwent a single interbody fusion at L5-S1, six patients at L4-S1, two patients at L3-S1, and one patient at L2-S1 in single lateral position (Fig. 4). Mean number of bony levels posteriorly instrumented was 2.9 ± 1.2 (range 2–6); all but three patients had a lower instrumented level of S1; patients 1, 3, and 9 were instrumented beyond S1 to the bilateral S2-alar-iliac level in lateral position using a previously described technique [11]. Mean total operative time for the group was 4:29 (hh:mm), with a mean of 3:13 for 1-level fusions and 4:38 for 2-level fusions. Mean estimated blood loss was 73 cc.

All patients had ALIF-type cages implanted at L5-S1 through oblique lateral minimally invasive incisions. Pre-operative and post-operative radiographic parameters for

Table 1 Summary of baseline characteristics of 17 patients included

	Number (%)
<i>Sex</i>	
Male	10 (59)
Female	7 (41)
Age	60.8 (range 30–80)
BMI	29.5 (range 20.4–39.9)
<i>Diagnosis</i>	
Deformity	2 (12)
Degenerative disc disease	15 (88)
<i>Fusion extent</i>	
One interbody level (L5-S1)	8 (47)
Two interbody levels (L4-S1)	6 (35)
Three interbody levels (L3-S1)	2 (12)
Four interbody levels (L2-S1)	1 (6)

all patients in this cohort are found in Table 3. Mean pre-operative radiographic parameters were L5-S1 segmental lordosis $11.2 \pm 7.6^\circ$ (range 3° – 26°), L1-S1 regional lordosis $50.5 \pm 18.2^\circ$ (range 29.5° – 83.1°), posterior disc height 4.2 ± 1.3 mm (range 1.9–6.5 mm), anterior disc height 9.3 ± 3.9 mm (range 4.6–15.7 mm), foraminal height 11.6 ± 3.2 mm (range 5.4–15.9 mm), sagittal vertical axis (SVA) 2.6 ± 3.9 mm (range -5.8 to 7.9 mm), pelvic tilt (PT) $17.7 \pm 8.6^\circ$ (range 8.3° – 38.2°), and pelvic incidence–lumbar lordosis (PI-LL) mismatch $4.2 \pm 14.2^\circ$ (range -11.9° to 28.5°). Preoperative LDI was normal in eight patients, hypolordotic in six patients, and hyperlordotic in three patients. Mean post-operative radiographic parameters were L5-S1 segmental lordosis $22.7 \pm 7.3^\circ$ (range 11° – 34°), L1-S1 regional lordosis $55.5 \pm 13.9^\circ$ (range 32.8° – 81.1°), posterior disc height 6.9 ± 2.0 mm (range 4.3–11.8 mm), anterior disc height 17.3 ± 3.9 mm (range 13.6–23.9 mm), foraminal height 14.6 ± 3.1 mm (range 9.2–18.4 mm), SVA 2.5 ± 3.2 mm (range -5.6 to 6.7 mm), PT $14.0 \pm 5.5^\circ$ (range 8.8° – 27.1°), and PI-LL mismatch $-0.8 \pm 10.7^\circ$ (range

Fig. 3 a Preoperative and b intraoperative CT showing placement of the L5-S1 anterior cage. Not shown is the ability on the same CT to confirm accuracy of pedicle screws

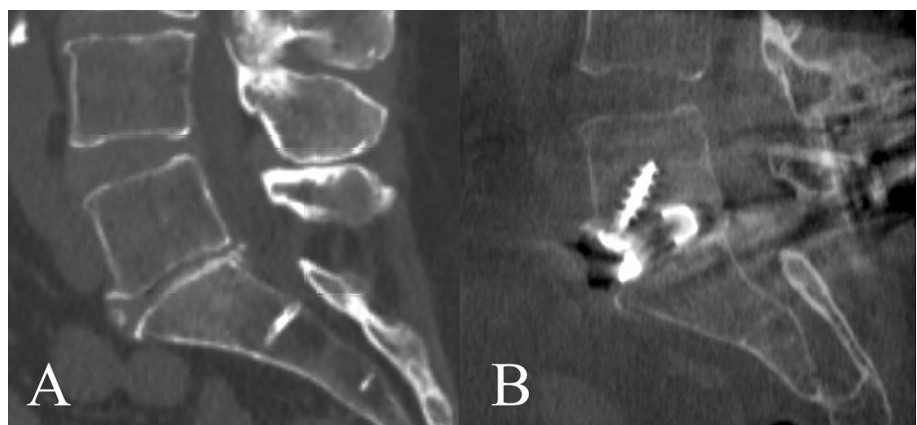
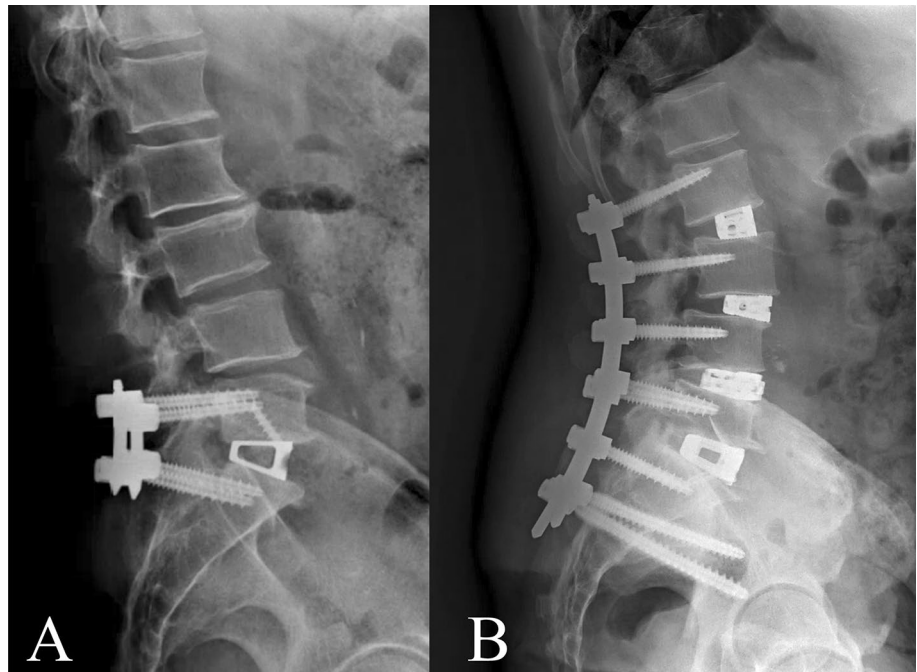


Table 2 Data regarding patient demographics and treatment

Pt	Age/sex	BMI	Procedure	Interbody levels	Operative time (hh:mm)	EBL	Discharge	LOS (d)	Follow-up clinical/radiographic (m)
1	70M	39.9	L3-S1 OLIF, L3-iliac PSF	3	6:42	100	ARU	5	8.1/6.0
2	69F	28.1	L4-S1 OLIF/PSF	2	3:54	75	Home	3	33.9/27.9
3	74M	24.8	L4-S1 OLIF, L4-iliac PSF	2	3:52	100	ARU	3	33.9/27.9
4	51M	32.9	L5-S1 OLIF/PSF	1	3:02	50	Home	4	28.8/28.3
5	66F	31.3	L5-S1 OLIF/PSF	1	3:31	75	Home	3	4.3/2.7
6	56M	32.5	L5-S1 OLIF/PSF	1	2:56	50	Home	1	25.2/18.3
7	34F	23.4	L5-S1 OLIF/PSF	1	2:32	30	Home	1	26.0/26.0
8	30M	24.4	L5-S1 OLIF/PSF	1	3:25	30	Home	3	16.2/15.9
9	59M	31.6	L2-S1 OLIF, L2-iliac PSF	4	8:48	150	ARU	6	11.2/11.2
10	76F	24.6	L3-S1 OLIF/PSF	3	7:09	100	Home	5	10.5/11.0
11	65M	25.1	L5-S1 OLIF/PSF	1	3:02	50	Home	2	9.4/10.0
12	52M	35.5	L4-S1 OLIF/PSF	2	4:45	75	Home	3	10.5/10.5
13	61F	27.3	L5-S1 OLIF/PSF	1	4:04	75	Home	2	6.7/6.4
14	80F	35.0	L4-S1 OLIF/PSF	2	5:18	50	Home	4	7.9/7.9
15	64F	20.4	L5-S1 OLIF/PSF	1	3:16	75	Home	3	7.3/7.3
16	60M	37.4	L4-S1 OLIF/PSF	2	5:28	75	Home	3	6.8/6.8
17	66M	26.6	L4-S1 OLIF/PSF	2	4:34	50	Home	3	6.3/6.3

Pt=patient, OLIF=oblique lumbar interbody fusion, PSF=posterior spinal fixation, LOS=length of stay, d=days, m=months, mm=millimetre, ARU=acute rehabilitation unit, EBL=estimated blood loss

Fig. 4 Lateral standing X-ray of **a** Patient 11 who underwent single position L5-S1 interbody fusion with posterior fixation and **b** Patient 9 who underwent L2-S1 interbody fusion with an L5-S1 ALIF cage and lateral single position posterior fixation from L2-iliac



–19.9° to 15.6°). Post-operative LDI was normal in 14 patients, hypolordotic in two patients, and hyperlordotic in one patient. Mean improvement in radiographic parameters were L5-S1 segmental lordosis $11.5 \pm 3.8^\circ$ (range 4° – 19°), L1-S1 regional lordosis $5.0 \pm 6.3^\circ$ (range -6.7° to 16.6°), posterior disc height 2.7 ± 1.9 mm (range -0.6 to 8 mm),

anterior disc height 8.0 ± 3.0 mm (range 1.6–12.7 mm), foraminal height 3.0 ± 1.7 mm (range 0.9–5.9 mm), SVA -0.1 ± 1.5 mm (range 4.5 to -2.8 mm), PT $3.7 \pm 6.0^\circ$ (range 23.4° to -1.5°), and PI-LL mismatch $-5.0 \pm 6.3^\circ$ (range 16.6° to -6.7°). Six patients (patients 1, 3, 5, 7, 9, 14) improved from an LDI of either hypolordotic or

Table 3 Data regarding patient preoperative and post-operative radiographic parameters

Pt	L5-S1 (°)		LDI		SVA (mm)		PT (°)		PI-LL (°)	
1	19	33	40	69	7.2	6.3	17.6	15.5	28.5	13.5
			Hypo	Normal						
2	6	12	43	44	5.6	6.7	11.8	11	6.7	4.9
			Hypo	Hypo						
3	2	11	33	63	6.5	6.3	30.5	27.1	21.6	15.6
			Hypo	Normal						
4	4	18	70	80	-5.8	-5.6	9.7	3.4	-18.3	-19.9
			Normal	Normal						
5	5	13	85	75	2.6	2.8	15	14.4	7.9	-0.7
			Hyper	Normal						
6	10	25	78	74	-2.5	0.3	8.3	9.3	-6.3	-11.6
			Normal	Normal						
7	3	22	45	63	1.5	1.8	8.5	7.7	-7.3	-14
			Hypo	Normal						
8	17	227	62	59	1.1	0.5	22.8	20.3	-3.9	-1.6
			Normal	Normal						
9	9	23	38	52	7.9	3.4	38.2	14.8	23.3	6.7
			Hypo	Normal						
-0	4	16	45	45	3.8	2.6	10.3	11.8	-9.4	-12.1
			Hypo	Hypo						
11	4	21	102	108	5.6	5.2	17.8	18.2	7	3.7
			Hyper	Hyper						
12	20	24	62	74	-1.4	0.6	18.7	14.7	-2.5	4.2
			Normal	Normal						
13	11	22	71	79	3.5	3.3	19.2	15.4	-4.4	-3.1
			Normal	Normal						
14	12	23	101	72	6.9	6.4	19.1	16.1	25.4	15.1
			Hyper	Normal						
15	22	34	73	76	-1.7	-0.4	11.6	8.8	1.6	-9.1
			Normal	Normal						
16	26	36	61	66	0.5	0.2	12	11.5	-11.9	-9.9
			Normal	Normal						
17	17	26	59	77	3.3	2.9	30.1	18	13.4	4.6
			Normal	Normal						

Hypo = hypolordotic (LDI < 50); Normal = LDI 50–80; Hyper = hyperlordotic (LDI > 80); mm = millimetre

hyperlordotic to normal, and there were no instances of LDI normal patients becoming imbalanced (Fig. 5).

Statistical analysis showed that the mean preoperative PT of $17.7 \pm 8.6^\circ$ was significantly improved post-operatively to $3.7 \pm 6.0^\circ$, $p = 0.021$. The preoperative PI-LL mismatch of $4.2 \pm 14.2^\circ$ also improved post-operatively to $-5.0 \pm 6.3^\circ$, $p = 0.0048$. There was no statistically significant improvement in the mean correction parameters for L5-S1 segmental lordosis ($p = 0.065$), LDI ($p = 0.085$), or SVA (0.841). To further examine LDI correction, we performed a second analysis on patients who were either hypolordotic or hyperlordotic preoperatively. Patients who were initially hypolordotic (mean LDI 40.7) improved significantly into the normal LDI range post-operatively (mean 56.0),

$p = 0.035$. Patients who were hyperlordotic preoperatively (mean 96.0) did not improve significantly into the normal LDI range (mean 85.0), $p = 0.39$.

Of 100 screws placed in lateral position using the robotics platform, there were three total breaches (two lateral grade 3, one medial grade 2) in two patients for a screw accuracy of 97.0%. These were both noted on the intraoperative CT spin and repositioned using navigated techniques with no post-operative clinical symptoms. There were no instances of patient repositioning, conversion to another interbody technique, abandonment of robotic use, blood transfusions, or use of post-operative drains. There were no major complications and the complete complication profile of the cohort is shown in Table 4. Minor complications included

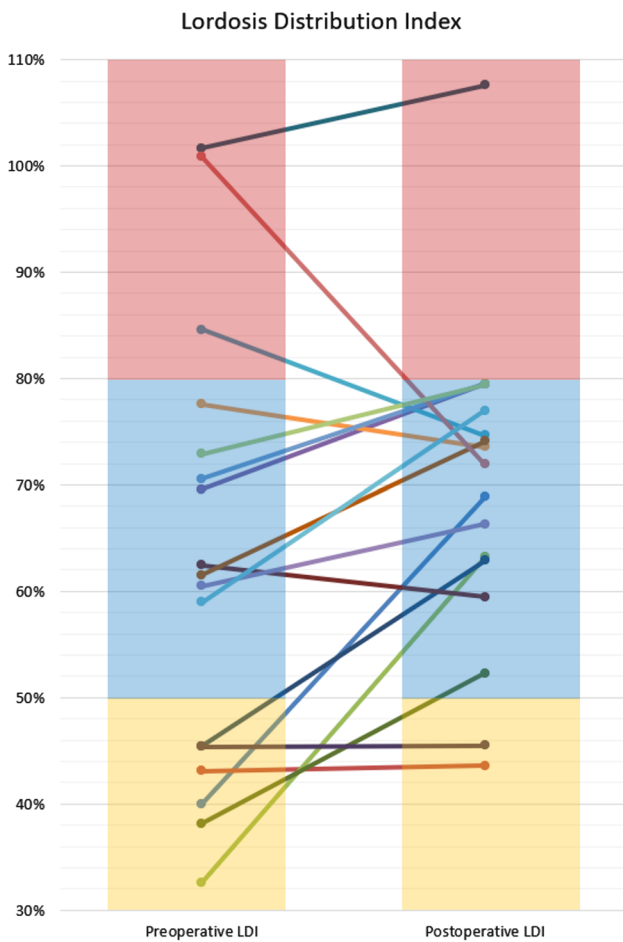


Fig. 5 Chart graph demonstrating six of nine patients that were maldistributed preoperatively became LDI normal post-operatively. All preoperative LDI normal patients remained so post-operatively

urinary retention (patient 3), prolonged anterior incisional pain which resolved at 8 weeks (patient 7), left hip flexor pain and weakness likely as a result of concomitant L2-5 OLIF cage placement (patient 9), anterior abdominal wall hernia (patient 10), post-operative delirium (patient 14), and delayed onset of radiculopathy which resolved with a short course of methylprednisolone (patients 11 and 15). Average length of stay was 3.2 ± 1.4 days (Table 2).

Discussion

Lordosis distribution index

Understanding the contribution of each lumbar arch to global lordosis of the lumbar spine is characterized by the lordosis distribution index (LDI), which demonstrates that 50–80% of lordosis is ideally represented in the L4-S1 level, considering each patient’s unique PI [12]. Both hypo

Table 4 Summary of complication profile of 17 patients included

	Number (%)
<i>Minor complications</i>	
Abdominal wall hernia	1 (7)
Delayed leg dysesthesias	2 (14)
Delirium	1 (7)
Hip flexor pain/weakness	1 (7)
Incisional pain	1 (7)
Urinary retention	1 (7)
Wound infection	0 (0)
<i>Major complications</i>	
Bowel injury	0 (0)
Neurologic injury	0 (0)
Vascular injury	0 (0)
Ureteral injury	0 (0)
Implant failure	0 (0)
Reoperation	0 (0)

and hyperlordotic deviations from the ideal LDI are associated with iatrogenic adult spinal deformity (ASD) after initial lumbar fusion, and may require significant revision [7]. Therefore, a careful consideration of the post-operative LDI when performing lumbar interbody fusion from L4-S1 is crucial to maintaining an ideal PT, PI-LL mismatch, and global sagittal lordosis [13]. A recent meta-analysis showed that ALIFs performed at L4-S1 yield an improvement of 6.4 degrees in segmental lordosis, and up to 9 degrees in global lordosis [14, 15]. Further, biomechanical studies have shown that ALIF at L5-S1 provides improve lordosis distribution in the lower lumbar arch, which may optimize global lordosis and reduce stress on posterior fixation rods [16]. These data suggest that ALIF-type approaches and large footprint interbody cages offer numerous advantages with respect to correcting lumbar lordosis and sagittal imbalance, as evaluated through the LDI.

Our study found that six of nine maldistributed patients improved to a normal LDI with single position lateral ALIF at L5-S1. We emphasize that no patient who was preoperatively LDI-normal became hypolordotic by LDI after surgical intervention, which can be a concern with other interbody techniques that may induce relative kyphosis at L5-S1 [17].

Lateral ALIF

First described in 1997, lateral ALIF provides an efficient operative corridor between the great vessel bifurcation similar to that accomplished a supine ALIF or between the psoas muscle, aorta, and inferior vena cava depending on the configuration of the patient’s vasculature [18]. Numerous advantages have validated this technique including reduced

operative time, blood loss, large spinal deformity correction, superior fusion rates compared to smaller cage footprints, and decreased post-operative pain [19, 20]. Comparison studies have suggested that a ALIF may be superior to a transforaminal approach (TLIF) for restoring disc height at the L5-S1 level in isthmic spondylolisthesis, and that lateral approaches may provide minimally invasive advantages over the traditional supine ALIF without compromising segmental correction [21]. Indeed, recent meta-analyses demonstrated that ALIF provides superior lumbar lordosis correction, and can be expected to provide a mean improvement of 4.67 degrees, and 2.0 ± 3.2 mm of disc height correction, when compared to other techniques [22, 23]. In our study, we found that our lateral ALIF experience yielded a segmental lumbar lordosis mean improvement of $11.6 \pm 4.0^\circ$, consistent with this reported literature.

Overall global and regional standing balance has been shown to improve with the ALIF approach [15]. We also report a mean improvement in overall regional and spinopelvic alignment with an improvement in PT of $-3.7 \pm 6.0^\circ$ and PI-LL mismatch of $5.0 \pm 6.3^\circ$.

Our group has previously explored the reported complications in the literature when performing the lateral ALIF at L5-S1 [24]. In our patient cohort, we found no major complications although there were several minor adverse events with two (abdominal wall hernia and prolonged incisional pain) that were directly related to this anterior approach.

Simultaneous robotic single position surgery

While the degree of correction to L5-S1 by lateral ALIF is quite favourable, further opportunity remains to increase the efficiency of this approach. A prior study showed favourable results through this smaller retroperitoneal exposure but these operations were performed in two stages, leading to higher EBL, surgical time, and complications [25]. To circumvent the challenges of patient reposition and increase operative efficiency, a single position lateral surgical technique was described in 2015 by which lumbar interbody fusion and percutaneous posterior fixation (LIF-PPS) are performed simultaneously [26]. A recent meta-analysis of several studies comparing single position LIF-PPS and LIF-PPS with repositioning, concluded that single position surgery yields lower operative time, lower EBL, lower fluoroscopic radiation dosage, and shorter length of stay [27]. We found in our series a favourable low EBL of 73 cc across the entire series, and operative times of 3:13 for 1-level fusions and 4:38 for 2-level fusions. There was expected prolonged operative times for patients with BMI of ≥ 35.0 kg/mm² (patients 1, 12, 14, 16). The longest operative time was 8:48 for patient 9 who underwent an L2-S1 OLIF with L2-iliac minimally invasive posterior spinal fixation in single

position for sagittal imbalance which was a unique case that has since been published as an operative video [28].

Comparison studies and propensity matched analyses have demonstrated that robotic systems improve surgical efficiency and decrease operative complications in a pooled multicentre cohort [6]. The development of techniques leveraging robotics to perform simultaneous posterior fixation in the lateral decubitus position have shown promising results regarding operative and radiographic outcomes. One report detailed SR-SPS using OLIF and reported a 95% accuracy of pedicle screw placement with favourable operative and patient outcomes, however, few cases of SR-SPS at L5-S1 were characterized [29]. A concern of earlier robotics systems was skive potential whereby the initial pilot drill would “slip” or “chatter” off an angled bony surface docking point and subsequently alter the entire subsequent paths of the tap and screw. Technologies now include high-speed burrs that rapidly decorticate the cortical landing zone to reduce the force needed to drill, as well as technical recommendations that advise air drilling down the robot guide so that all tools (drill, tap, and screw) are already spinning as they touch the bone. These advances have notably reduced screw malpositioning at our institution.

The present study expands on this SR-SPS technique especially as it applies to the lateral ALIF at the L5-S1 level. We found this technique to combine the advantages of a large interbody footprint from an ALIF cage at L5-S1, the benefits of robotics for posterior fixation in the lateral position, and the efficiency of single position surgery. We found that this simultaneous surgical workflow provided excellent screw placement accuracy of 97.0%. Radiographic outcomes were favourable as measured by LDI, SVA, PT, and PI-LL mismatch. There were no major complications involving neurologic, vascular, bowel, or ureteral structures. Although not the focus of this paper, we also demonstrate the ability to instrument from L2 to the ilium in single lateral position with robotic assistance for applicable and appropriate cases. To the best of our knowledge, a characterization of SR-SPS with lateral ALIF at L5-S1 has not yet been described.

Limitations

There were several limitations to this study that are common to retrospective case series including errors in electronic charting, measurement errors, selection biases, single-centre study, single-surgeon study, and lack of a control group. We were not able to include a discussion of patient-reported outcome measures (PROMs) as several patients did not have preoperative data, and so this paper is structured as a radiographic paper. To this end, we do rely on data demonstrating that realignment of radiographic parameters correlates with improved PROMs [30]. The study cohort was relatively small given the nature of this initial experience

and description of the technique; while improvements in PT, PI-LL mismatch, and hypolordotic LDI correction were statistically significant, improvements in L5-S1 lordosis and SVA only approached statistical significance and may reflect the small numbers in this study. The inclusion of other surgeons and surgical centres into a larger multicentre study would allow for the analysis of technique variability which may increase the external validity of our results.

Conclusion

We describe here a series of patients who underwent minimally invasive single position lateral ALIF at L5-S1 with robot-assisted posterior fixation via a simultaneous two-surgeon technique. Overall, the lordosis distribution index improved for hypolordotic patients, pelvic tilt and PI-LL mismatch were improved, and there were no major complications. Lateral ALIF at L5-S1 may be a powerful approach to achieve favourable correction at a single surgical level.

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Declarations

Conflict of interest None of the listed authors has any conflicts to report, financial or otherwise, which may have influenced the content or publication of this work.

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