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ORIGINAL ARTICLE

Clinical and radiographic outcomes following 120 consecutive patients undergoing prone transpsoas lateral lumbar interbody fusion

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Abstract

Purpose The prone transpsoas approach is a single-position alternative to traditional lateral lumbar interbody fusion (LLIF). Earlier prone LLIF studies have focused on technique, feasibility, perioperative efficiencies, and immediate postoperative radiographic alignment. This study was undertaken to report longer-term clinical and radiographic outcomes, and to identify learnings from experiential evolution of the prone LLIF procedure.

Methods All consecutive patients undergoing prone LLIF for any indication at one institution were included ($n=120$). Demographic, diagnostic, treatment, and outcomes data were captured via prospective institutional registry. Retrospective analysis identified 31 'pre-proceduralization' and 89 'post-proceduralization' prone LLIF approaches, enabling comparison across early and later cohorts.

Results 187 instrumented LLIF levels were performed. Operative time, retraction time, LLIF blood loss, and hospital stay averaged 150 min, 17 min, 50 ml, and 2.2 days, respectively. 79% of cases were without complication. Postoperative hip flexion weakness was identified in 14%, transient lower extremity weakness in 12%, and sensory deficits in 10%. At last follow-up, back pain, worst-leg pain, Oswestry, and EQ-5D health state improved by 55%, 46%, 48%, and 51%, respectively. 99% improved or maintained sagittal alignment with an average 6.5° segmental lordosis gain at LLIF levels. Only intra-psoas retraction time differed between pre- and post-proceduralization; proceduralization saved an average 3.4 min/level ($p=0.0371$).

Conclusions The largest single-center prone LLIF experience with the longest follow-up to-date shows that it results in few complications, quick recovery, improvements in pain and function, high patient satisfaction, and improved sagittal alignment at an average one year and up to four years postoperatively.

Keywords LLIF · Prone-lateral · PTP · Minimally invasive · Proceduralization · Decubitus

Introduction

Prone transpsoas lateral lumbar interbody fusion (LLIF) is an evolution of the LLIF experience that began in earnest following the publication in 2006 of the retroperitoneal transpsoas technique and early outcomes [1]. That technique and the experience that followed described the patient as positioned in lateral decubitus to allow for orthogonal access to the lumbar spine. Despite the growing utilization, reported minimally invasive benefits, and successful outcomes of LLIF [2, 3], many surgeons have remained resistant to adopting the technique, likely due to a low but concerning incidence of postoperative thigh symptoms [2], or perhaps due to practical challenges associated with the unconventional lateral decubitus position. In particular, lateral decubitus positioning limits the ability to impart lordosis, perform multilevel instrumentation, and decompress neural elements. This can be particularly important in revision situations where simultaneous access to the anterior and posterior columns is needed to perform osteotomies, anterior and posterior releases, and to revise instrumentation. Thus, lateral decubitus LLIF has required re-positioning the patient—at times more than once—to complete the

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procedure [4]. The necessity to re-position the patient prolongs surgery time [5], which may increase the risks associated with extended anesthesia [6–8], and poses logistical concerns to hospital staff.

The impetus behind the prone transpsoas LLIF technique [9] was to address the concerns that have resulted in limited surgeon adoption, while at the same time preserving the advantages of LLIF, including minimally invasive benefits [2, 3], large cage footprint with high fusion rates [10–12], indirect neural decompression [13, 14], improved lordosis [15, 16], and good long-term outcomes [2, 3]. Prone positioning has the added benefits of familiar initial patient positioning and eliminating the need for re-positioning while facilitating the completion of circumferential procedures as needed, including posterior fixation, direct decompression, posterior releases, and revision of prior hardware. Moreover, lumbar lordosis is more naturally accommodated [17, 18], demonstrated in postoperative lordosis gains [19–21]. However, most reports to-date following prone LLIF have focused on feasibility, intraoperative efficiencies, and perioperative outcomes [19, 22–26].

The current study reports the radiographic and patient-reported clinical outcomes following prone transpsoas LLIF in 120 patients, representing a single surgeon's experience with the technique since its inception and continuing through its evolution to include procedure-specific tools that streamlined the procedure for reproducible results. That learning curve is highlighted as a comparison of pre- and post-proceduralized outcomes.

Materials and methods

Patient cohort

At a single institution, all consecutive patients undergoing prone transpsoas LLIF for any indication between mid-2019 and mid-2022 were captured via prospective institutional registry to document demographic, diagnostic, and procedural details, as well as clinical (patient-reported) outcomes, and radiographic alignment measures. Retrospective database analysis identified 31 prone lateral approaches prior to proceduralization using procedure-specific positioners and retractor and 89 proceduralized surgeries, enabling comparison across early and later cohorts.

Operative technique

The prone transpsoas technique has been described previously [9]. Cases taking place between May 2019 and June 2020 (i.e., the pre-proceduralization or "PrLat-pre" group) were performed using a 3-blade retractor designed for LLIF in the lateral decubitus position (Squadron®, ATEC Spine, Carlsbad, CA), prototype and first-generation patient positioners, as well as early software versions of saphenous nerve somatosensory evoked potentials (saphSSEP) monitoring (SafeOp™, ATEC Spine). Surgeries taking place after June 2020 were performed using a purpose-designed retractor for prone transpsoas LLIF (Sigma™-PTP, ATEC Spine), specialized prone positioners (PTP Patient Positioner, ATEC Spine), and updated versions of saphSSEP monitoring. The procedures performed using the proceduralized technologies comprise this study's post-proceduralization or "PrLat-post" group.

In both groups (PrLat-pre and PrLat-post) of the current series, the patient was positioned prone over a Jackson table with the abdomen hanging freely, the hips positioned neutral to slightly extended, and the knees in gentle flexion. Care was taken to avoid pressure on the anterior inferior iliac crest to reduce the risk of femoral nerve compression. Modular positioners were applied to optimize coronal bending and access to the L4-5 level (Fig. 1) [20].

Access was carried out through a single skin and fascial lateral incision to target the index level and retroperitoneal blunt dissection to gain safe access to the psoas muscle. Safe digital access was accomplished by first palpating the quadratus lumborum muscle and pushing the peritoneal contents anteriorly while developing the potential space. The psoas then was palpated directly and an initial triggered-EMG-monitored dilator was inserted through the muscle to the annulus. Progressive monitored dilators were then used to identify a safe corridor to access the disc space. Notably, these aforementioned steps for retroperitoneal and transpsoas access to the disc are similar whether in prone or traditional lateral decubitus. An advancement in the safety of lateral-approach surgery is the utility of saphenous SSEP for continued monitoring of the health of the femoral nerve during the remainder of the procedure, after safe access is achieved using triggered EMG [27]. Once the retractor was docked and expanded (Fig. 2), disc space preparation and interbody fusion were completed utilizing a large-footprint porous titanium interbody spacer (IdentiTi®, ATEC Spine) and autologous bone marrow concentrate (ART BMC, Celling Biosciences, Austin, TX) with a synthetic extracellular matrix (Solumn IV, Celling Biosciences). Once the interbody fusion construct was completed, the posterior component of the surgical procedure was performed without re-positioning of the patient. In some cases, surgical planning favored a posterior-first approach, which was easily accommodated via the prone single-position set-up. Percutaneous pedicle screws and/or lateral antimigration plates were used to supplement the anterior column fusion in all cases.

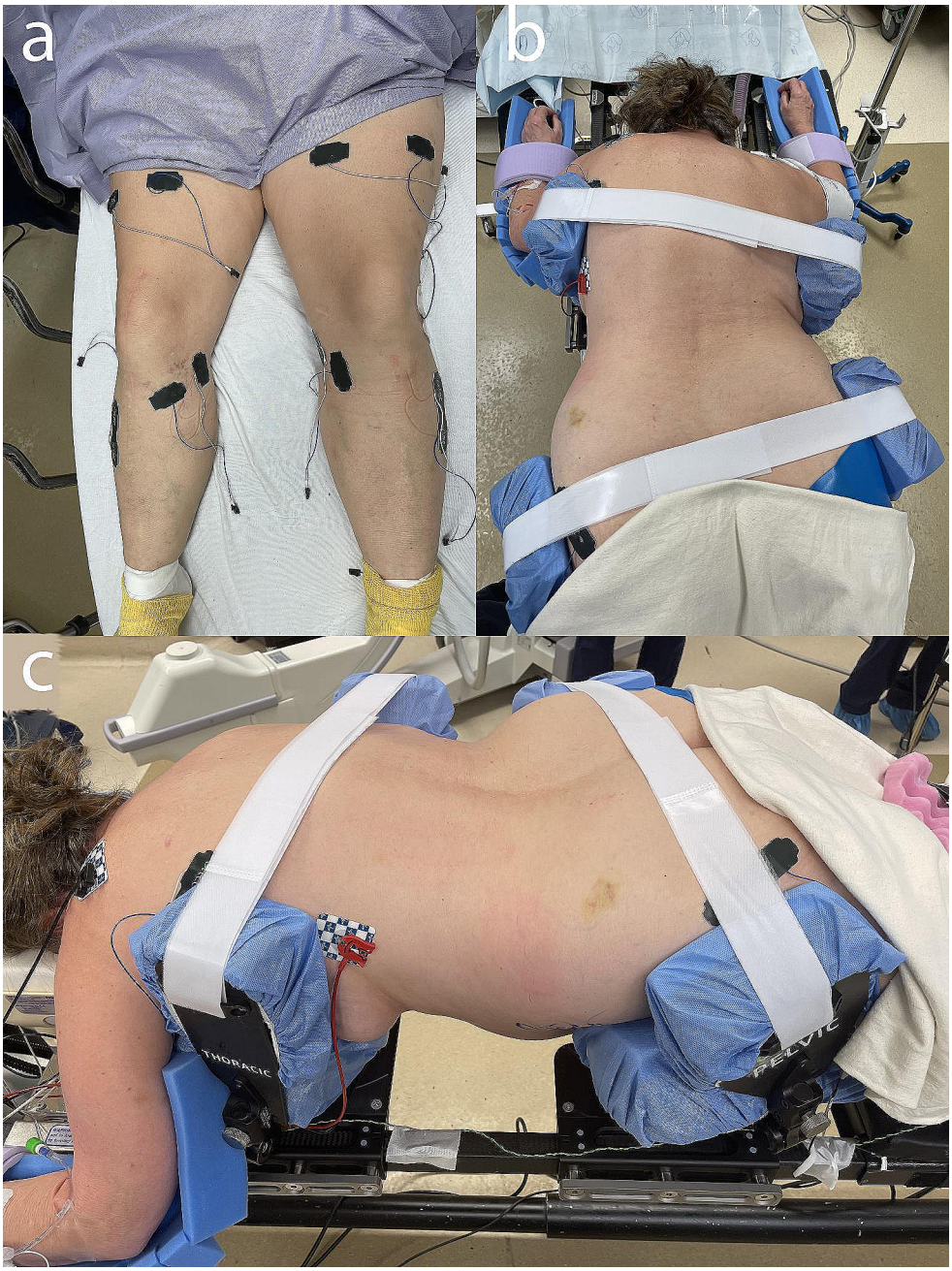

Fig. 1 Intraoperative photograph showing patient preparation for the prone transpsoas LLIF procedure, including the placement of surface electrodes for intraoperative neuromonitoring (EMG recording electrodes on the quadriceps, anterior tibialis, and biceps femoris muscles; stimulating electrodes at the saphenous nerve inferomedial to the patella) (**a**), and positioning on the PTP patient positioner (**b** and **c**), comprising separate thoracic and pelvic bolsters which attach to a Jackson-style surgical table, can be adjusted to snugly enclose the patient using adjustable side paddles and straps, and can be rotated away from one another to create coronal bend and expansion of the lateral space between the ribs and the iliac crest for effective access to L4-5 and above

Outcomes evaluated

All data was collected prospectively through an institutional review board-approved registry effort. Patient and procedural information such as age, sex, body mass index (BMI), comorbidities, medical and surgical history, diagnosis, levels treated, operative time, blood loss, complications, and length of hospital stay were captured as standard of care. Patient-reported outcomes measures (PROMs) were prospectively collected at preoperative and all postoperative clinic visits per standard of care (6 weeks, 3 months, 6 months, 12 months, and annually thereafter), including measures of pain (visual analog scale, VAS), function (Oswestry disability index, ODI), and quality of life (EQ-5D). Patient satisfaction was also collected at all postoperative visits.

Neutral standing radiographs of the lumbar spine and/or long scoliosis films were collected preoperatively and at the same subsequent time intervals. Images were measured to calculate spinopelvic alignment parameters (Surgimap, Nemaris Inc., New York, NY). Radiographic measures included disc angle (DA), pelvic tilt (PT), pelvic incidence (PI), lumbar lordosis (LL), L4-S1 lordosis, and SVA where applicable. Normal alignment targets were defined as

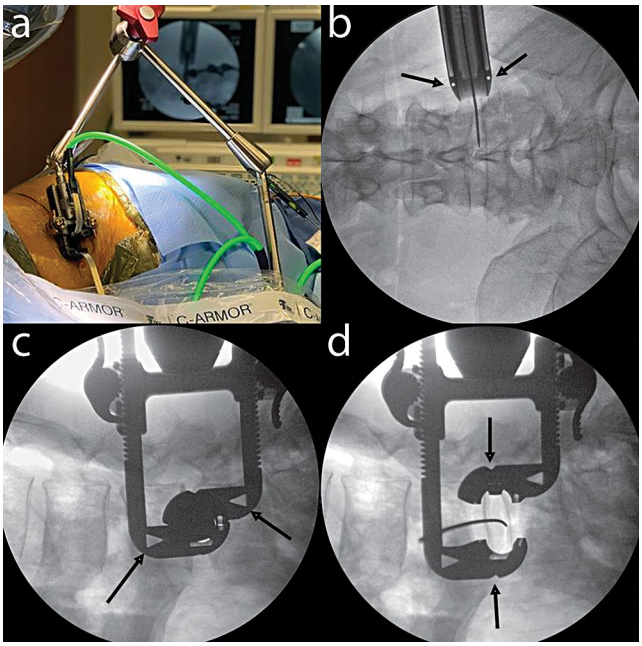

Fig. 2 Intraoperative photograph (**a**) showing the specialized retractor used for prone transpsoas LLIF. It is a lighter, two-bladed system that provides more rigid retraction due to its single-piece construction, and is affixed to the ipsilateral bed via a shorter, and therefore more stable, articulating arm. Its design includes several features to help confirm fluoroscopically that its position is in-line with (**b** - arrows) and orthogonal to (**c, d** - arrows) the spine, and the aperture (**d**) can be customized as needed depending on initial docking location by virtue of independent movement of the anterior and posterior blades, which creates an exposure preferentially over the disc, minimizing psoas retraction trauma, and protecting the critical structures anterior and posterior to the retractor blades

PI-LL < 10°, PT < 25°, SVA < 50 mm, and L4-S1 lordosis of at least 60% of LL [28].

Statistical analysis

Statistical analysis included descriptive statistics (mean, standard deviation, range) and comparisons of means or proportions (via analysis of variance, matched-pair t-test, or Chi-square test as appropriate for continuous or categorical variables) and were made using JMP statistical software (SAS Institute, Cary, NC) with a significance level set at 0.05.

Results

Patient cohort

The total cohort of 120 patients (PrLat-pre: 31, PrLat-post: 89) were 64% female, averaged 64 years of age (range: 26–84 years), and had a mean BMI of 31 (range: 18–51). Comorbidities included diabetes in 27% and smoking in 11%. 38% of all patients were taking opioids preoperatively. Differences in patient characteristics between the PrLat-pre and PrLat-post groups are shown in Table 1; none of the differences were significant ($p > 0.05$).

Indications for surgery included primary diagnoses of spondylolisthesis (32%), sagittal and coronal deformity (32%), adjacent and primary disc degeneration (23%), and post-laminectomy instability, disc herniation, and/or pseudoarthrosis (12%). Primary indication for the PrLat-pre cohort was predominantly scoliosis (29% vs. 8% for PrLat-post), while primary indication for the PrLat-post cohort was predominantly sagittal malalignment (24% vs. 6% for PrLat-pre), reflecting an increasing appreciation for the ability to correct sagittal alignment with growing prone LLIF experience, and especially following introduction of the proceduralized systems.

Procedural details

One LLIF procedure was aborted due to body habitus-related neuromonitoring challenges; the patient underwent a standard posterior laminectomy and fusion, facilitated by the existing prone position. No other procedure was aborted due to challenges with the prone LLIF approach itself. In the remaining 119 patients, a total of 187 levels were treated (average: 1.6 level/patient; range: 1–5 levels/patient). Of all procedures, 76% were inclusive of the L4-5 level. Concomitant posterior procedures included 1–7 levels/patient of posterior fixation, 38% with direct decompression, 8% with osteotomies, and 10% revision of prior hardware. Overall operative time averaged 150 min, with an average 17 min of psoas retraction time. Estimated LLIF blood loss averaged 50 ml, and hospital stay averaged 2.2 days.

Table 1 Patient characteristics for the total cohort of 120 patients, and categorized by the pre- and post-proceduralization groups

	PrLat pre-proceduralization	PrLat post-proceduralization	Total Cohort	*p*-value
Female, *n* (%)	58%	52%	54%	0.6776
Mean age, years (range)	67.5 (31–84)	62.8 (26–80)	64.0 (26–84)	0.0510
Mean BMI, kg/m^2 (range)	31.9 (20.7–40.0)	31.0 (18.4–51.0)	31.3 (18.4–51.0)	0.5057
Diabetes (%)	35%	24%	28%	0.2459
Smoking (%)	7%	12%	11%	0.7270
Opioid use (%)	25%	44%	39%	0.1172

BMI body mass index

**P*-values < 0.05 are considered significant

Differences in procedural details between the pre- and post-proceduralization groups are shown in Table 2. The percentage of cases that included concomitant posterior procedures such as direct decompression, osteotomies/releases, and hardware revision was statistically significantly higher in the post-proceduralization group, again reflecting an increasing appreciation for the ability and efficiency of single-position circumferential treatment, when indicated, as the operative surgeon's prone LLIF experience grew. Importantly, the introduction of the tools to facilitate prone transpsoas LLIF corresponded with an overall shorter mean psoas retraction time ($p = 0.0371$). This could also be attributed to increased experience over time; however, the trend of retraction time decreasing with case count was not statistically significant ($p = 0.0878$).

Complications

Surgical complications occurred in 21% of patients, and included 2 intraoperative cage repositionings (both to correct a too-posterior initial position), 1 partial anterior longitudinal ligament (ALL) rupture, 1 durotomy (during posterior procedure), 1 epidural hematoma, 1 posterior wound infection, 1 pseudoarthrosis. There were no vascular, peritoneal, bowel, or other visceral injuries in any patient. While the overall incidence of surgical complication was not different between pre- and post-proceduralization groups ($p = 0.4285$), it is worth noting that the single inadvertent ALL rupture occurred in the pre-proceduralization group, reflecting a common gravitational challenge with systems designed for lateral decubitus use being repurposed for prone use. Neither the ALL rupture nor the correction of cage position during the index procedures resulted in any postoperative sequelae, and other complications were minor with no lasting effects.

Transient postoperative hip flexion weakness was identified in 14% overall (16% in PrLat-pre vs. 14% PrLat-post, $p = 0.7341$), transient lower extremity (quadriceps) weakness in 12% (13% in PrLat-pre vs. 11% PrLat-post, $p = 0.3034$), and sensory deficits in 10% (13% in PrLat-pre vs. 9% PrLat-post, $p = 0.4535$). Among patients with quadriceps weakness, all recovered within 6 weeks to 12 months postoperatively except one patient, who demonstrated a dense (grade 0/5) and prolonged quadriceps weakness, which ultimately improved to grade 3/5 at three years and to grade 4/5 at 4 years post-op (most recent follow-up). That deficit occurred in an otherwise unremarkable case of a single-level L4-5 procedure in a 46-year-old female with grade I spondylolisthesis. Notably, it was one of the very first cases in the series (pre-proceduralization) and the only case in the series that did not include saphenous SSEP monitoring (third-party intraoperative monitoring reported no abnormalities). Psoas retraction time was 22 min, and there were no other intraoperative indications of this potential outcome.

Secondary surgeries included 2 adjacent-level decompressions, 1 epidural hematoma evacuation, and 1 pseudoarthrosis revision in a patient with degenerative scoliosis who had undergone L4-5 prone LLIF with a lateral plate and no posterior fixation. He was revised 10 months after the index procedure with another prone LLIF ipsilateral to the index surgery with a larger implant and pedicle screws.

Clinical outcomes (PROMs)

Follow-up averaged 16 months (range: 1.5 to 44 months). At last follow-up, 26% of patients were using opioids. Back pain, worst-leg pain, ODI, and EQ-5D health state improved by an average 55%, 46%, 48%, and 51% respectively, all statistically significant improvements from pre- to last post-operative follow-up ($p < 0.0001$). The minimum clinically important difference (MCID) of one or more PROMs was met by 85% of all patients. There were no statistically significant differences in PROMs between the pre- and

Table 2 Procedural details for the total as-treated cohort of 119 patients, and categorized by the pre- and post-proceduralization groups

	PrLat pre-proceduralization	PrLat post-proceduralization	Total Cohort	*p*-value
Total number of levels, n	46	141	187	
LLIF levels per patient, mean (range)	1.5 (1–4)	1.6 (1–5)	1.6	0.5725
Inclusive of L4-5, %	74%	76%	76%	0.8044
Direct decompression, %	26%	42%	38%	0.0159*
Osteotomies/releases, %	0%	8%	8%	< 0.0001*
Revision of previous surgery, %	0%	10%	10%	< 0.0001*
Average psoas retraction time, min	19.2	15.8	16.7	0.0371*
Total OR time, min	131	156	150	0.1116
LLIF blood loss, ml	52.2	48.7	49.6	0.7710
Total blood loss, ml	111.7	138.8	131.7	0.2578
Length of hospital stay, days	2.1	2.2	2.2	0.4622

LLIF lateral lumbar interbody fusion, *OR* operating room

**P*-values < 0.05 are considered significant

Table 3 Changes in average patient-reported clinical outcomes measures from preoperative to last postoperative visit (average 16 months; range 1.5 to 44 months) characterized by the pre- and post-proceduralization groups

	PrLat pre-proceduralization	PrLat post-proceduralization	Total Cohort	*p*-value
Δ ODI	-22.0 (50%)	-22.2 (47%)	-22.1 (48%)	0.9608
Δ VAS back	-3.5 (49%)	-4.1 (53%)	-4.0 (55%)	0.3826
Δ VAS worst-leg	-3.0 (48%)	-3.4 (46%)	-3.3 (46%)	0.6701
Δ EQ-5D health state	-42.6 (64%)	-34.8 (48%)	-36.6 (51%)	0.3205

ODI Oswestry disability index, *VAS* visual analog (pain) scale, *EQ-5D* EuroQol Questionnaire – 5 Domains

**P*-values < 0.05 are considered significant

Table 4 Changes in radiographic alignment parameters from preoperative to last postoperative visit (average 16 months; range 1.5 to 44 months)

	Pre-op	Post-op	*p*-value
PI	55.3°	55.3°	1
DA	-4.5°	-11.1°	< 0.0001*
LL	-46.9°	-50.5°	< 0.0001*
PI-LL	11.9°	8.7°	< 0.0001*
L4-S1	-28.6°	-30.7°	< 0.0001*
PT	20.4°	19.1°	0.0022*
SVA	65.3 mm	59.5 mm	0.4813

PI pelvic incidence; DA disc angle, *LL* lumbar lordosis, *PI-LL* pelvic incidence – lumbar lordosis mismatch, *L4-S1* lordosis between the L4 and S1, *PT* pelvic tilt, *SVA* sagittal vertical axis

**P*-values < 0.05 are considered significant

Table 5 Segmental lordosis (disc angle) at preoperative and last postoperative visits, characterized by level

	T12-L1	L1-L2	L2-L3	L3-L4	L4-L5
Pre-op	1.5°	3.1°	3.8°	4.8°	4.9°
Post-op	6.2°	9.1°	10.1°	11.0°	11.8°
p-value	< 0.0001*	< 0.0001*	< 0.0001*	< 0.0001*	< 0.0001*

**P*-values < 0.05 are considered significant

post-proceduralization groups ($p > 0.05$) (Table 3). Across the total cohort, 90% said they were improved, 85% were satisfied, and 85% would elect the surgery again.

Radiographic outcomes (sagittal alignment)

There were statistically significant changes in each calculated alignment parameter from preoperative to last postoperative imaging, with the exception of PI and SVA (Table 4), and including significant segmental lordosis (disc angle) correction at all LLIF-treated levels (Table 5). Notably, not all patients required sagittal alignment correction preoperatively (Table 6); however, 99% improved or maintained sagittal alignment with an overall average 6.5° segmental (disc angle) lordosis gain at prone LLIF levels.

Case examples

Representative case examples are shown in Figs. 3 and 4. The first (Fig. 3) is a 58-year-old female registered nurse who presented with back and leg pain. Preoperative MRI showed central stenosis, facet effusions, and anterior plexus location. Lateral imaging showed an L4-5 mobile spondylolisthesis (grade I in supine MRI; grade II in standing lateral radiograph) and significant sagittal mal-alignment with a PI-LL mismatch of 27.5°. The patient underwent prone LLIF with an anterior docking through the psoas to avoid an anterior plexus and to remain protected from the great vessels. Indirect decompression of the neural elements was achieved through correction of the slip and fixated with percutaneous posterior instrumentation. Postoperative lateral standing radiograph showed marked improvement in sagittal alignment, with 9.2° increase in segmental lordosis at the L4-5 disc level and a correction of the PI-LL mismatch from 27.5° to 4.6°. The patient reported to be much improved in both back and leg symptoms and very satisfied with her results postoperatively.

The second example (Fig. 4) is a 67-year-old male with a two-year history of back and bilateral leg pain with numbness and tingling. He had difficulty walking and achieved some (but not total) relief with bending forward. Preoperative imaging showed significant stenosis, particularly at L4-5, with degenerative lumbar discs and a pathologic loss of sagittal alignment: PI-LL mismatch of 19.1° The objectives of surgery included attaining physiologic sagittal alignment via three-level LLIF in the prone position to facilitate concomitant direct (posterior) decompression of

Table 6 Percentages of patients failing to meet sagittal alignment goals, shown at preoperative and at last postoperative visits (average 16 months; range 1.5–44 months), and identifying percentages that improved/ were corrected versus those preserved similar to preoperative baseline, or worsened compared to preoperative baseline. **P*-values < 0.05 are considered significant

	Pre-op	Post-op	*p*-value	Corrected	Preserved	Worsened
PI-LL > 10°	53.8%	24.4%	< 0.0001*	30.3%	68.9%	0.8%
PT > 25°	30.5%	11.8%	< 0.0001*	20.2%	78.2%	1.7%
SVA > 50 mm	71.7%	48.0%	0.0214*	17.6%	82.4%	0%

PI pelvic incidence, *LL* = lumbar lordosis, *PT* = pelvic tilt, *SVA* = sagittal vertical axis

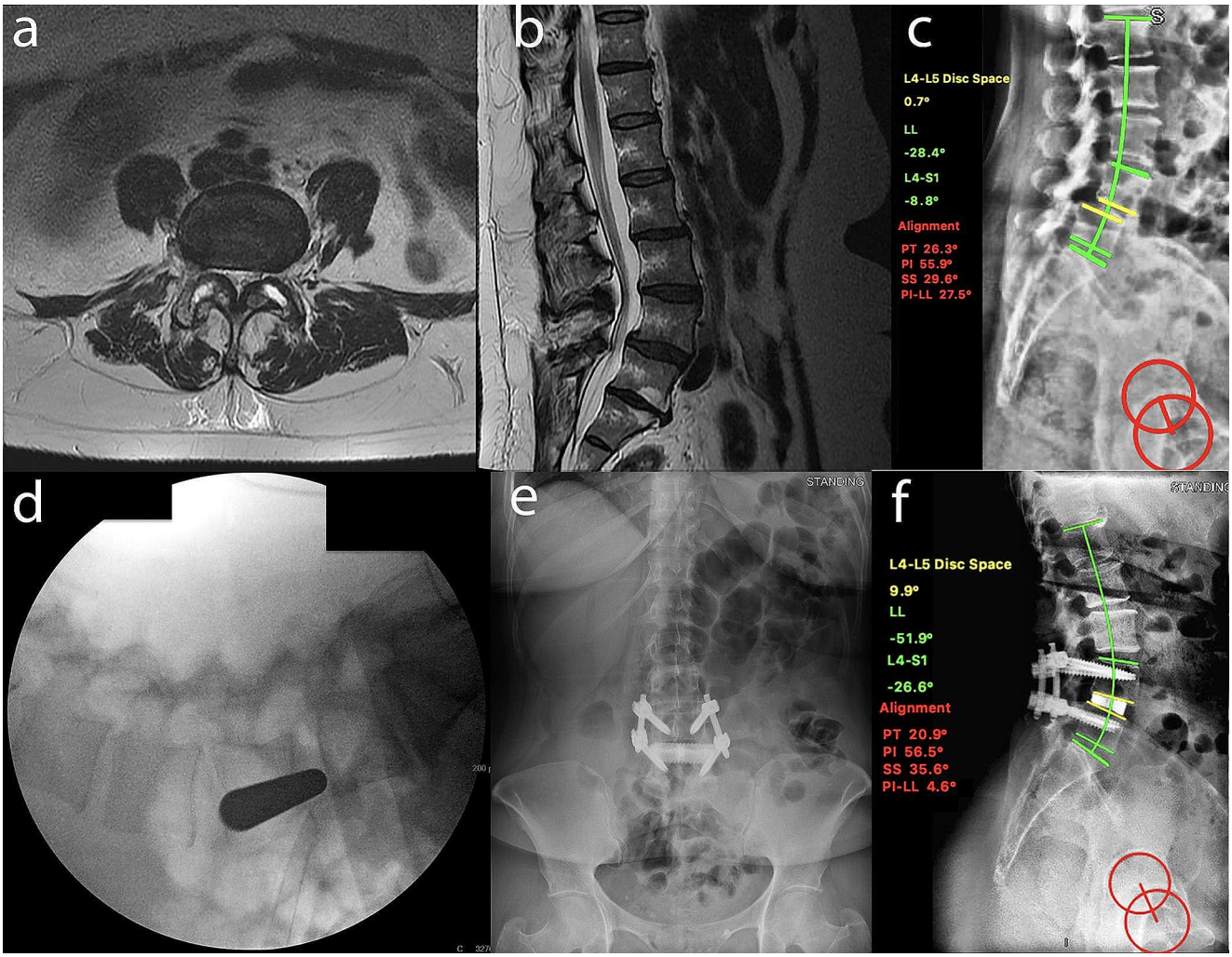

Fig. 3 Preoperative L4-5 axial (**a**) and sagittal (**b**) MRI, and lateral standing radiograph (**c**); intraoperative lateral fluororadiograph (**d**); and postoperative anterior-posterior (**e**) and lateral (**f**) radiographs of a patient with back and leg pain due to grade II spondylolisthesis with central stenosis who underwent prone transpsoas LLIF at L4-5

his severely stenotic L4-5 segment and percutaneous posterior instrumentation. Surgery was carried out as planned, with 25 cc blood loss during the three-level prone LLIF and 100 cc total. He did sustain an incidental durotomy that was repaired during the index surgery. At one-year postoperative, his imaging shows good spinal alignment (with an improvement in lumbar lordosis of nearly 15° and PI-LL mismatch of only 4.8°). Moreover, he indicated that he had no back or leg pain and his neurogenic claudication had resolved, and he was no longer taking any analgesic or opioid medications.

Discussion

Techniques for single-position lateral-approach surgery have been purported by lateral-approach surgeon advocates [5, 29, 30], mainly with the intent to avoid having to reposition the patient between anterior- and posterior-column procedures. Patient re-positioning prolongs operative/anesthesia duration, increases logistical demands, and exposes the patient to potentially increased injury [5–9]. However, single-position surgery in the lateral decubitus position, while avoiding patient re-positioning, has its own unique set of problems associated with requiring the surgeon to perform the posterior portion of the surgery in the lateral position. The majority of lateral interbody fusion constructs are supplemented with posterior pedicle screw fixation. Placement of pedicle screw instrumentation in the lateral position is technically demanding, especially in multilevel

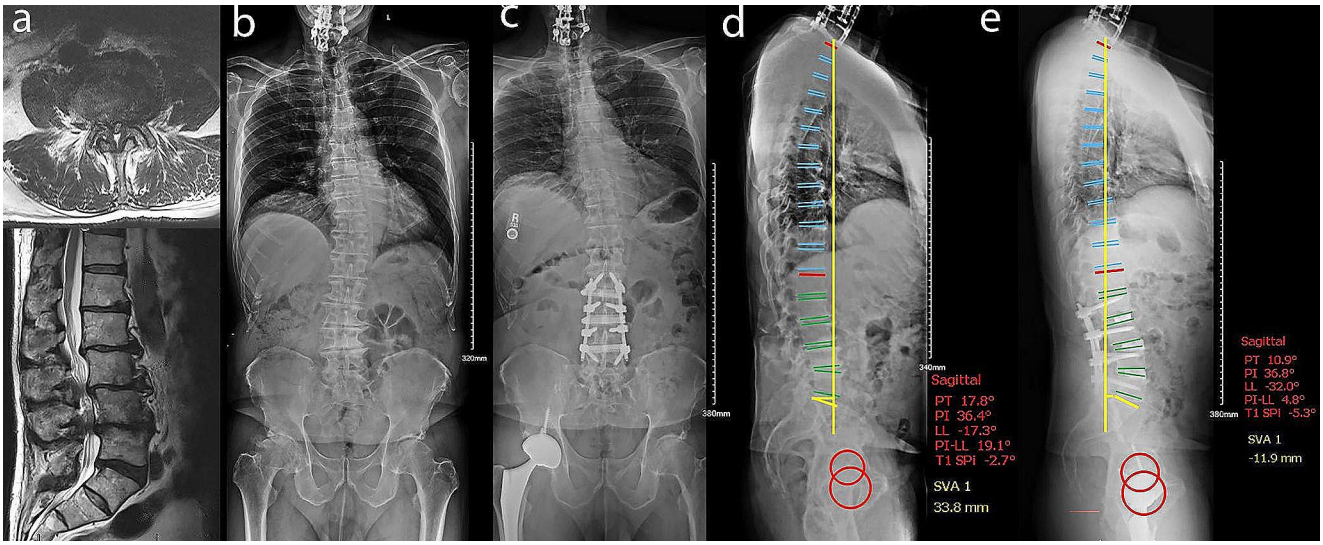

Fig. 4 Preoperative L4-5 axial and sagittal MRI (**a**); preoperative (**b**) and postoperative (**c**) anterior-posterior standing radiographs; and preoperative (**d**) and postoperative (**e**) lateral standing radiographs of a patient with back and leg pain due to multi-level degeneration and significant stenosis who underwent prone transpsoas LLIF from L2 to L5 with direct (posterior) decompression at L4-5 and percutaneous pedicle fixation

instrumentation [31], and has been associated with higher pedicle breach rates [32]. In addition, the ability to obtain optimal lordosis is limited [33].

In general, addressing the posterior column in the lateral decubitus position is not familiar to most spine surgeons. Lumbar decompression in the lateral position is not ergonomic and poses challenges in multilevel and wider laminectomy cases [29, 30]. In a multi-center study of single-position circumferential lumbar fusions, Buckland et al. advocated for the efficiencies of a single lateral decubitus positioning, but excluded patients from the retrospective review if they required open decompression [29]. A review article on the topic provides a decision-tree algorithm for single-position lateral procedures and concludes that the "feasibility of direct decompression in the LD [lateral decubitus] has yet to be reported and thus PSPS [prone single-position surgery] may be superior when direct decompression is to be performed." [30] The opportunity to easily employ concomitant posterior-approach procedures such as direct decompression, when indicated, and simplifying the clinical decision-making related to when indirect decompression may or may not be enough for a patient with radicular symptoms is a primary advantage of the prone transpsoas LLIF approach.

In deformity cases where the posterior column may have to be addressed (e.g., through osteotomy/releases) prior to the lateral procedure, it may be necessary to reposition the patient twice [34] or to stage the multiple procedures [35]. In addition, unless the ALL is released, optimal lordosis may be difficult to establish when solely relying on disc preparation and interbody fusion with the patient in lateral decubitus [33, 36–38]. Segmental lordosis gains following lateral decubitus LLIF have been reported in the range of 2.6° [36] to 4.4° [38]. ALL release, while an effective procedure [34, 35, 37, 39], is technically demanding and not without added risk [40]. It is well appreciated that prone positioning results in greater lumbar lordosis than positioning in lateral decubitus [17, 18], with both gravity and hip flexion and/or extension playing a significant role [17, 41]. Pimenta et al. reported an average segmental lordosis gain of 6.1° in a series of prone transpsoas LLIF patients [19]. In a propensity-matched comparison of traditional LLIF versus prone LLIF procedures, Amaral et al. showed an average change in segmental lordosis of 1.9° for traditional LLIF versus 6.6° for prone transpsoas LLIF ($p = 0.02$) [42]. The current study's finding of an average of 6.5° improvement in segmental lordosis following prone transpsoas LLIF is very consistent with these prior reports.

Other outcomes in the current study, including the frequency and type of complications as well as mid- to long-term patient-reported outcomes are consistent with the authors' experience with traditional LLIF surgery and with prior reports of prone LLIF. To the authors' knowledge, this is the largest series with the longest follow-up to report on patient-reported outcomes following prone transpsoas LLIF. Wellington et al. reported significant improvements in ODI and back and leg VAS in a series of 82 patients with 3 months follow-up [43]. The current study found significant improvements in all PROMS at an average of 16 months, but some nearing four years of follow-up.

Although the clinical profile of LLIF in either prone or lateral decubitus may be similar, prone transpsoas LLIF has

additional advantages over lateral decubitus LLIF, including, firstly, that the surgical plan can be changed without affecting the procedural flow and can be fit to the best interest of the patient to optimize outcome (as occurred in one patient whose prone LLIF was abandoned in favor of posterior decompression and fusion due to unreliable neuromonitoring baselines). Additionally, the posterior column can be addressed *prior* to LLIF if needed, such as in irreducible grade II L4-5 spondylolisthesis, when there is a need for osteotomy, or when treating adjacent segment disease requires revision or extension of previous instrumentation. Prone positioning also allows for simultaneous access to the anterior and posterior columns if needed. For these reasons, prone transpsoas LLIF more practically offers the fulfillment of surgical efficiency sought after with single-position surgery.

Experiential learnings

A common criticism by deformity surgeons is the performance of LLIF in the "wrong" position. Due to those factors and the attractive prospect of optimizing alignment while retaining the concept of "single-position surgery," the possibility of performing LLIF in the prone position appears to be very attractive. In fact, an increasing number of reports of "prone lateral" surgeries are emerging from several institutions. One of the obstacles is the attempted adaptation of the already existing surgical equipment used for LLIF in the lateral decubitus position to its use in the prone position [22]. The pre-proceduralization (PrLat-pre) group in the current study was representative of those cases. The current authors' experience began with the use of a 3-bladed retractor designed for lateral decubitus surgery, prototype positioners, and tape, in addition to early versions of saphenous SSEP neuromonitoring. What was learned from that experience was that LLIF in the prone position has specific requirements. As opposed to the lateral decubitus position, gravity works against retractor orientation and stability. This has required a lighter yet more rigid retractor system, with a more posteriorly placed lateral incision and more rigid table attachment to help minimize anterior drift. In addition, specialized anterior and posterior shims further increase stability between the retractor and the patient. In order to maximize lordosis and access, especially at the L4-5 level, specialized padded positioners were also designed and shown to improve L4-5 access over high-riding iliac crests in comparison to laterally bending over a breaking surgical bed [20]. More advanced automated saphSSEP monitoring was used in post-proceduralization cases aided by early experience [27].

Study limitations

The patient population studied is a heterogeneous blend of multiple degenerative and deformity conditions, ranging from simple single-level cases to complex revisions and multi-level deformity corrections. While that heterogeneity likely increased the variability of outcomes, these collective results underscore the breadth of applicability and the reproducibility of the technique across a range of real-world challenges.

The current study reflects a single surgeon's experience who had extensive transpsoas LLIF experience in the lateral position prior to adopting prone LLIF. As such, the results may not represent the learning curve that surgeons new to lateral approaches may experience. However, this author's early struggles with repurposed technologies can and should be avoided in favor of purposefully designed procedure-specific solutions that have herein shown an ability to apply the prone transpsoas LLIF approach to patients requiring more complex strategies, including direct decompression, posterior releases, and revisions, as well as efficiencies in overall psoas retraction time.

Conclusions

The largest single-center prone transpsoas LLIF experience with the longest follow-up to-date shows that it results in few complications, quick recovery, improvements in pain and function, high patient satisfaction, and improved sagittal alignment at an average one year and up to four years postoperatively. These mid- to long-term outcomes are consistent with this institution's prior lateral decubitus LLIF experience, and highlight the broad applicability and effectiveness of the proceduralized prone transpsoas LLIF procedure.

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Declarations

Conflict of interest PM Van Pevenage has no conflicts. AG Tohmeh is a consultant for Alphatec Spine, the manufacturer of the devices described in this study, but received no financial support or remuneration related to the publication of this article. KM Howell is an employee of Alphatec Spine. All authors have full control of the primary data and allow the journal to review the data if requested.

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