The minimally invasive lateral lumbar interbody fusion (LLIF) approach to treat degenerative spinal conditions has grown in popularity. Studies have demonstrated satisfactory patient outcomes and appropriate restoration of lordosis, with an acceptable safety profile.\(^1,2\) For maximal stability, interbody placement is supplemented with pedicle screw fixation to achieve circumferential fixation and fusion.\(^3,4\)

However, a logistical drawback to the LLIF approach is a reliance on multiple patient positions during surgery for interbody access. Particularly, the LLIF approach may require lateral decubitus positioning of the patient for interbody access first, followed by prone positioning for percutaneous screw placement. Recently, surgeons have been interested in pursuing single-position surgery to reduce surgical time and to improve the efficiency of surgical flow by reducing the number of repositioning episodes for the patient.\(^5,7\)

Despite some adoption of this technique by neurosurgeons, data are limited regarding the success of single-position surgery with the patient in a lateral position. Early studies have suggested decreased accuracy with the lateral placement of bilateral pedicle screws,\(^7,8\) although other authors have noted reduced operative times.\(^7,9,10\) Several au-
Postoperative radiographs and CT imaging. Pre- and postoperative quality-of-life outcome scores, such as those on the Oswestry Disability Index and visual analog scale for back pain, were collected.

Surgical Technique
Positioning

The patient is positioned prone on a standard Jackson table for the LLIF (Fig. 1A). Hip pads are placed at the posterior-superior iliac spine or slightly below to maximize lordosis. As with lateral decubitus positioning, adhesive tape is used to stabilize the patient on the table (Fig. 1A and B). However, it is critical to use a contralateral bolster to provide tension against the lumbar spine during graft placement (Fig. 1B) akin to table breaking or placement of a roll to facilitate crest and rib separation, particularly for patients with a high iliac crest. Taping is used across the chest and at the level of the pelvis to provide stability; tape is then placed on the lateral chest wall (aimed superiorly) and iliac crest (aimed posteriorly) to further separate ribs and iliac crest, as well as to tension the skin for easier soft-tissue dissection on the side of approach. Notably, our choice of surgical approach is similar to SL approaches. Our preference is from the side of concavity or the side with more amenable psoas anatomy; if there is equipoise with respect to approach side, our preference is the right side because of the vessel anatomy.

Imaging

Standard fluoroscopy with the C-arm is used to identify the level of interest. Use of CT navigation is an alternative for LLIF. First, an anteroposterior image is obtained, and the Jackson table is adjusted (tilt and Trendelenburg) to facilitate an orthogonal position. Next, a lateral radiograph is obtained, and the bed is arranged so that the level of interest is orthogonal with the facing wall. An incision is marked on the lateral side in a standard fashion (Fig. 1C).

Operative Procedure

The operative field is draped to include the posterior aspect of the lumbar spine, bilateral posterior-superior iliac spine (intended for neuronavigation tracker placement), and lateral access corridor (Fig. 1D). A retroperitoneal transpsoas approach is performed to bluntly access the lateral aspect of the spine in a standard fashion, with the surgeon seated on a stool on the ipsilateral side of the surgical approach (Fig. 2A). The dilator is then placed perpendicular to the spine of the prone patient (Fig. 2B), respecting the standard “safe zones” previously described with radiographic confirmation using lateral fluoroscopy. Sequential dilation through the psoas muscle is performed (Fig. 2C), and electromyography thresholds are then obtained in a directional manner in a standard fashion, respecting the previously described threshold limits. Notably, in our experience, the psoas muscle appears to be displaced posteriorly compared to its position in the lateral decubitus position. This resulted in a tendency for more posterior docking despite acceptable electromyography threshold values. The retractor is then docked and attached to the retractor arm (Fig. 2D); notably the retractor...
arm is attached to the bed on the ipsilateral side. Retractor positioning is then verified with lateral and anteroposterior fluoroscopy. Next, a standard wide discectomy with contralateral annulotomy is performed (Fig. 2E). Implant trialing and placement is then performed in a standard fashion, with care not to over-distract and cause endplate fracture (Fig. 2F). Implants are selected on the basis of patient anatomical factors and bone quality; implants typically provide $10^\circ$–$15^\circ$ of lordosis and 8–10 mm in height.

The second stage includes the placement of percutaneous pedicle screws using CT navigation with sentinel fluoroscopic imaging (Fig. 2G). First, the tensioning tape is removed to reduce strain on the soft tissues and decrease curvature of the spine. Next, an iliac crest tracker is placed and intraoperative CT is performed. Navigation is then used in a standard fashion to place percutaneous pedicle screws with anteroposterior fluoroscopic imaging to verify accuracy.

### Statistical Analysis

Data are reported as number (percent) and mean ± standard deviation. Retractor times and electrophysiologically significant thresholds are expressed as the means for each level. A comparison of preoperative and immediate postoperative radiographs was performed. Statistical significance was established using a threshold of $p < 0.05$. SPSS Statistics for Windows (version 24; IBM Corp.) was used for all analyses.

### Results

#### Cadaveric Feasibility Study

Two cadaveric specimens were used to assess the PL approach to the spine. With the cadaveric torsos in the prone position, access to the L1–2 through L4–5 levels was possible without the need for angled instruments. Access to L1–2 required dilation between T11 and T12 ribs. No vascular or intestinal injury was appreciated on inspection, nor did incidental anterolateral ligament release occur. Implant sizes ranged from 8 to 12 mm in height and 55 to 60 mm in length. Postintervention radiographic inspection did not reveal iatrogenic endplate damage. Interbody placement was at designated safe working zones (zone 3 at L1–2 through L3–4; zone 3 at L4–5); dissection demonstrated dilation through the psoas muscle anterior to the lumbar plexus in both cases (Fig. 3).

#### Clinical Case Series

Twelve patients meeting the study inclusion criteria underwent attempted single-position PL interbody placement with standard prone percutaneous pedicle screw fixation; 11 patients successfully underwent the PL surgery and 1 patient was transitioned from the PL to SL position for the final surgery. The mean age of patients undergoing PL surgery was 61 ± 16 years, and 6 of the 11 patients (54%) were women. The diagnoses for PL interbody placement among the 11 PL patients were spondylolisthesis (7 of 11 [64%]), degenerative disc disease (3 of 11 [27%]), and adjacent segment disease (1 of 11 [9%]). The mean preoperative radiographic parameters for the 11 PL patients were a
pelvic incidence of $52° \pm 15°$, lumbar lordosis of $52° \pm 14°$, pelvic incidence–lumbar lordosis mismatch of $4° \pm 11°$, and sagittal vertical axis of $3.1 \pm 1.9$ cm (Table 1). The mean weight of the 11 PL patients was $76.9 \pm 23$ kg, and the mean BMI was $25.8 \pm 4.8$; the patient who was unable to undergo PL surgery had a body weight of 108 kg and BMI of 35.

### Surgical Details

Surgical results are presented for the 11 patients who successfully underwent the PL approach. Lateral transpsoas interbody fusion with patients in the PL position was performed at 14 levels: L2–3 (2 of 14), L3–4 (6 of 14), and L4–5 (6 of 14). The approach was performed from the right side in 8 of 11 patients (73%) and from the left side in 3 of 11 patients (27%). The most commonly used cage was $10°$ ($9 of 14$ levels). The mean case duration was $175 \pm 101$ minutes with a mean estimated blood loss of $17.5 \pm 14$ ml. The mean retractor time per level was $15 \pm 6$ minutes. The mean overall fluoroscopy time was $10^\text{th} \pm 9^\text{th}$ minutes. The mean electrophysiological threshold values are reported in Table 2. Additional percutaneous pedicle screws were performed across 13 levels in 10 patients. The mean overall fluoroscopy time was $267 \pm 98$ seconds, with a mean radiation emission dose of $171 \pm 60$ mGy. No perioperative subsidence was noted on intraoperative radiographs.

Among all 12 patients, one experienced postoperative urinary retention that resolved on admission. Six patients described transient pain described before they were discharged from the hospital. Two patients had transient postoperative thigh pain that resolved before they were discharged from the hospital.

### Table 1: Demographics and radiographic values for patients in the clinical case series

| Case No. | Sex | Age (yrs) | Dx | Surgery | Pedicle Screws | Case Duration (mins) | Weight (kg) | BMI (kg/m²) | L2–3 | L3–4 | L4–5 | Retractor Time (mins) | Preop | Postop |
|----------|-----|-----------|----|---------|----------------|---------------------|-------------|-------------|-------|-------|------|-----------------------|-------|--------|
| 1        | M   | 67        | DDD| L2–3 stand-alone | NA              | 70                  | 75           | 30          | 15    | 75    | 30   | 58  | 42  | 5.2 | 16 |
| 2        | F   | 41        | DDD| L3–4 XLIF | L3–4            | 180                 | 56           | 19          | 14    | 79    | 11   | 62  | 70  | 2.6 | 6 |
| 3        | F   | 49        | S   | L5–1 ALIF, L4–5 XLIF | L4–1 S1         | 360                 | 44           | 18          | 11    | 79    | 11   | 62  | 70  | 2.6 | 6 |
| 4        | M   | 69        | S   | L5–1 ALIF, L2–5 XLIF | L2–1 S1         | 240                 | 108          | 35          | 28    | 13    | 10   | 55  | 50  | 2.4 | 14 |
| 5        | F   | 78        | ASD | L3–4 XLIF | L3–5            | 140                 | 62           | 22          | 14    | 45    | 0    | 45  | 45  | 0   | 0 |
| 6        | F   | 68        | S   | L5–1 ALIF, L3–5 XLIF | L3–1 S1         | 360                 | 66           | 23          | 11    | 53    | 20   | 68  | 68  | 2.0 | 0 |
| 7        | M   | 71        | DDD | L2–4 XLIF stand-alone | NA              | 150                 | 96           | 28          | 28    | 21    | 11   | 30  | 29  | 1.9 | 5 |
| 8        | M   | 35        | S   | L4–5 XLIF | L4–5            | 110                 | 72           | 21          | 10    | 59    | 53   | 59  | 53  | 5.2 | 0 |
| 9        | M   | 67        | S   | L3–4 XLIF | L3–4            | 112                 | 114           | 29.8        | 8     | 45    | 49   | 45  | 49  | 4.0 | 3 |
| 10       | F   | 67        | S   | L3–5 XLIF | L3–5            | 240                 | 87.5         | 31          | 19    | 41    | 51   | 41  | 51  | 6.9 | 12 |
| 11       | M   | 72        | S   | L4–5 XLIF | L4–5            | 120                 | 99.7         | 31          | 19    | 42    | 38   | 42  | 38  | 3.0 | 0 |
| 12       | F   | 56        | S   | L4–5 XLIF | L4–5            | 90                  | 74           | 30          | 10    | 58    | 63   | 58  | 63  | 0   | 0 |

ALIF = anterior lumbar interbody fusion; ASD = adjacent segment disease; CC = coronal Cobb angle; DDD = degenerative disc disease; Dx = diagnosis; LL = lumbar lordosis; NA = not available/not applicable; PI = pelvic incidence; S = spondylolisthesis; SVA = sagittal vertical axis; XLIF = extreme lateral interbody fusion.

* Approach for patient was converted from PL to SL approach.

TABLE 1. Demographics and radiographic values for patients in the clinical case series

FIG. 3. Cadaveric procedure including prone positioning of the dilator (A) and retractor (B). Anteroposterior (C) and lateral (D) radiographs showing interbody placement.
resolved within 7 days. The mean length of stay was 2 ± 2 days.

Outcomes

The mean follow-up was 59 ± 29 days. Early postoperative radiographic values are reported in Table 1. The mean lumbar lordosis increased to 53° ± 11°, the sagittal vertical axis increased to 3.3 ± 1.6 cm, and the coronal Cobb angle decreased to 1.3° ± 1.3°. Postoperative MRI and CT imaging demonstrated well-positioned interbodies at all levels, without dorsal to ventral angulation; no immediate postoperative or perioperative subsidence was observed. No lateral or medial pedicle breaches were observed on postoperative CT imaging (0 of 46 pedicle screws) with pedicle screw fixation. The mean preoperative Oswestry Disability Index was 55.1 ± 30.4 and improved to 28.5 ± 18.0 (p = 0.03) after surgery, and the mean preoperative back pain score was 6.0 ± 2.3 and improved to 1.6 ± 0.8 (p < 0.001) at the early follow-up.

Illustrative Case

A 35-year-old man (case 8) presented with a long-standing history of low-back pain and unilateral radiculopathy that was not responsive to conservative management. Imaging demonstrated an L4 bilateral pars defect with resultant mobile spondylolisthesis (Fig. 4). The patient underwent a prone right-sided LLIIF with posterior percutaneous fixation. He was positioned as previously described for a PL approach, with a hip pad placed on the contralateral side to provide counterpressure; tape was used to provide a slight opening of the space between the rib cage and iliac crest, along with tensioning of the skin for easier dissection. The first stage involved the lateral interbody fusion; standard dissection was performed through the soft tissues, and care was taken to mobilize the retroperitoneal contents as described in previous studies. The retractor was docked with radiographic verification, and the interbody fusion was performed in 10 minutes, 15 seconds. Next, an iliac crest–based intraoperative tracker was placed, and intraoperative CT was performed. Percutaneous pedicle screws were placed with navigation

TABLE 2. Mean surgical times and electrophysiological values per level

| No. of Levels | Retractor Time (mins) | Anterior EMG Threshold (mA) | Posterior EMG Threshold (mA) | Subsidence |
|---------------|-----------------------|-----------------------------|------------------------------|------------|
| L1–2          | 0                     | —                           | —                            | —          |
| L2–3          | 2                     | 21.5 ± 9.1                  | 40 ± 0                       | 32 ± 11.3  |
| L3–4          | 6                     | 14.4 ± 4.9                  | 38 ± 3                       | 25 ± 11    |
| L4–5          | 6                     | 12.8 ± 3.8                  | 21 ± 8                       | 12 ± 9     |

EMG = electromyography.

FIG. 4. Case 8. Example of single-position lateral interbody fusion at L4–5. A: Preoperative lateral radiograph demonstrating L4–5 spondylolisthesis. B: Intraoperative lateral radiograph demonstrating dilator placement at zone 2/3 with acceptable electromyography thresholds. C: Intraoperative lateral radiograph demonstrating final titanium implant location. D: Preoperative anteroposterior radiograph. E: Intraoperative anteroposterior radiograph demonstrating docked retractor with shim placement at L4–5. F: Intraoperative anteroposterior radiograph demonstrating placement of the implant across the L4–5 disc space without subsidence.
assistance and the use of sentinel fluoroscopy. Lastly, reduction of the spondylolisthesis was performed with rod fixation and final tightening.

Discussion

While the use of the lateral approach corridor to the lumbar spine has outcomes comparable to those for posterior-only approaches such as transforaminal lumbar interbody fusion, SL positioning presents a logistical challenge when attempting circumferential fusion. The lateral single-position surgery variation facilitates a more streamlined workflow; however, authors have described the technical challenges involved with placing pedicle screws in the lateral position and difficulty when addressing 3 or more interbody fusion levels. We posit that performing the transpsoas approach with patients in the PL position leverages the advantage of the lateral minimally invasive technique, without the need for repositioning, and represents a maximally streamlined approach toward single-position surgery.

In the current paper, we present our findings from a cadaveric feasibility study and the early clinical experience of a single surgeon using this prone single-position technique to address degenerative spinal disease (Fig. 5). We noted successful and effective interbody fusion with PL positioning across 14 levels in 11 patients, along with pedicle screw placement across 13 levels in 10 patients. We aborted the PL approach in 1 patient and converted to an LLIF in the SL position because the patient’s abdominal girth exceeded the maximum capacity of our instruments, although his BMI of 35 was within the range of other patients in our sample. Furthermore, the patient’s abdominal girth made it difficult to adequately palpate the psoas muscle during the approach. Given the potential for a colon injury with poorly controlled dilation through the psoas muscle, the decision was made to abort the PL approach in this case because of safety concerns. This may be an interesting phenomenon associated with prone positioning, which, unlike lateral positioning, results in more soft-tissue accumulation between the skin and lumbar spine. Notably, in subsequent cases, we were able to overcome soft-tissue concerns (with an enlarged incision and greater dissection); however, in the future, we will give more attention to abdominal girth and adipose distribution on preoperative examination.

Several studies have described a single-position approach to minimally invasive surgery for the lumbar spine with patients in the lateral decubitus position. Blizzard and Thomas performed a retrospective review of 72 consecutive cases of 1- to 2-level LLIF or oblique LLIF with bilateral pedicle screw fixation. The authors noted an average screw placement time of 5.9-min/screw, with a 5.1% breach rate and 2.8% reoperation rate for symptomatic malpositioned screws. In particular, these authors noted the advantage of the lateral minimally invasive technique, without the need for repositioning, and represents a maximally streamlined approach toward single-position surgery.

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noted that lateral positioning for pedicle screw placement has a limited working corridor between the patient and the C-arm and advocated the use of guidewire-less screw systems. Sellin et al.8 noted a 14% lateral breach rate in 4 patients who had undergone single-position surgery with lateral percutaneous pedicle screw placement; the authors noted that all breaches occurred on the “down side” and could be attributed to poor patient positioning. The authors also reported that all breaches required a return to surgery for repositioning and noted that in 1 case bilateral pedicle screws were planned but could not be placed because of challenges with patient positioning. Ziino et al.19 described a shorter time with single-position surgery than that with dual-position surgery across 42 patients but also reported a higher likelihood of unilateral screws in single-position surgery (19% of patients) than in dual-position surgery (0% of patients). These authors also reported a 4.7% rate of return to surgery for screw repositioning (2 of 42 patients).

As a result of the nonstandard positioning associated with lateral single-position surgery, several authors have described a decrease in surgical time but significant technical challenges with screw placement.7–10

The alternate approach, prone-position surgery, was recently described by Lamartina and Berjano20 with a comparison between SL decubitus positioning and the prone approach. These authors similarly noted successful implantation in the majority of cases across 7 levels in 7 patients. They reported 133 ± 26 minutes for total operative duration, with a mean retractor time of 25.6 ± 13 minutes. While we did not measure the prone positioning time or compare it to times for SL decubitus positioning, we similarly observed an anecdotal trend toward shorter setup and positioning times. Similarly, the majority of our surgical cases focused on the L3–4 and L4–5 levels, but we did also operate on L2–3 levels, with an increased duration of retractor exposure likely owing to the slightly more challenging anatomy. However, comparatively, we did not experience any episodes of intraoperative cage subsidence. While we did not evaluate surgical outcomes in the current study, we did note a rate of postoperative hip pain that was similar to that published by Lamartina and Berjano,20 which appeared similarly transient. Overall, we agree that such prone positioning presents an attractive option for streamlined surgical solutions.

Theoretical advantages of prone positioning include positional lordosis if needed, the opportunity for direct decompression if needed, and the facilitation of a more natural and easier approach for screw placement (Table 3), along with potential hemostatic benefit, as previously suggested by other authors.11 In addition, the prone position presents, in our opinion, more amenable positioning for the use of navigation—the patient appears more secure in the prone position than in the lateral—with greater points of fixation and fewer chances of losing accuracy with rotary movements of the upper compared to the lower spine; this may provide improved fidelity of navigation and improved accuracy of screw placement. However, the current study is not designed to validate this concept.

Notably, we did not experience any anterior displacement of tools or instrumentation with patients in the prone position, as we had initially expected. Rather, the psoas muscle appears to be shifted posteriorly, possibly because of hip extension when the patient is positioned prone on a Jackson table as compared to hip flexion, which typically occurs when the patient is in the lateral position. Thus, somewhat counterintuitively, with PL positioning the placement of the dilution tube and instrumentation tends to migrate posteriorly when compared to placement in the SL position. In our experience, we noted an anecdotal trend toward higher electromyography thresholds with PL positioning than with SL positioning. Notably, we did not observe any tendency for implants to be placed anteriorly or with a dorsal to ventral angulation on postoperative imaging.

In our view, the PL positioning does not replace the SL positioning for LLIF, but in select patients, it can be a viable alternative that potentially increases efficiency and decreases operative time. We believe PL positioning is indicated in cases in which patient anatomy is amenable and in patients who are not large or morbidly obese. In our experience, it appears that body weight and distribution of adiposity are more critical than the observed BMI. We would recommend that, for more challenging anatomy (e.g., high crest, obesity, or transitional anatomy), surgeons default to the more familiar SL positioning until experience with the PL position is attained. This paper presents the largest clinical series published to date on the PL variant of the lateral approach. Although not the primary objective of the paper, this early experience provisionally demonstrates that this approach is safe, feasible, and reproducible.

**Study Limitations**

This study has several key limitations. First, the study has a retrospective design without a comparison group. As a result, we were unable to compare the prone single-position surgery to a lateral decubitus single-position surgery or dual-position alternatives in terms of surgical timing, accuracy, or patient outcome data. However, the primary objective of the study was to describe our initial experience and to complement the existing literature regarding prone positioning. Additionally, we did not perform quantitative or comprehensive measurements of surgical time—particularly time-saving elements that included positioning or time per screw placed. Lastly, our study describes only the short-term peroperative experience and

| Advantage                          | Prone                      | Lateral                      |
|------------------------------------|----------------------------|------------------------------|
| Navigation                         | Slight advantage           | Equivalent                   |
| Direct decompression or facetectomies (simultaneous) | Slight advantage | No advantage                 |
| Screw placement                    | Substantial advantage      | Equivalent                   |
| Positional lordosis                | Slight advantage           | Equivalent                   |
| ALIF (simultaneous)                | No advantage               | Equivalent                   |
| Patient obesity                    | Equivalent                 | Slight advantage             |

ALIF = anterior lumbar interbody fusion.
complications for patients and does not include extensive long-term patient-level outcomes. While initial postoperative neurological deficits were evaluated, no long-term patient-level outcome data were analyzed. We feel that future prospective studies with larger sample sizes are needed to fine-tune our surgical workflow, optimize lateral access circumferential fusion, and provide an accurate comparison to traditional and other single-position variants for a wide variety of patients (e.g., those with obesity, a high crest, or transitional anatomy).

Conclusions

Prone positioning for the lateral approach appears to be a viable and exciting option for minimally invasive spine surgery. Although future studies are needed, our initial experience indicates that the prone position is both safe and effective.

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Disclosures

Dr. Turner is a consultant for NuVasive and SeaSpine. Dr. Uribe is a consultant for, receives royalties from, and has direct stock ownership in NuVasive and is a consultant for Misonix and SI-BONE.

Author Contributions

Conception and design: Uribe, Godzik. Acquisition of data: Xu, de Andradia Pereira, Whiting. Analysis and interpretation of data: Uribe, Godzik, Ohiornhenu. Drafting the article: de Andradia Pereira. Critically revising the article: Walker, Whiting, Turner. Reviewed submitted version of manuscript: Uribe. Statistical analysis: Godzik, Whiting. Administrative/technical/material support: Turner. Study supervision: Uribe, Turner.

Supplemental Information

Videos

Video Abstract. https://vimeo.com/445620664.

Correspondence

Juan S. Uribe: c/o Neuroscience Publications, Barrow Neurological Institute, St. Joseph’s Hospital and Medical Center, Phoenix, AZ. neuropub@barrowneuro.org.