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# Single-Position Extreme Lateral Lumbar Interbody Fusion with Percutaneous Pedicle Screw Fixation Utilizing O-arm Navigation

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**Research Article**

**Keywords:** Extreme lateral interbody fusion, O-arm navigation, Percutaneous pedicle screw fixation, Radiation dose, Radiation exposure, Single-position surgery

**Posted Date:** April 3rd, 2026

**DOI:** https://doi.org/10.21203/rs.3.rs-9178248/v1

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**Additional Declarations:** No competing interests reported.

Original Research Article

# Single-Position Extreme Lateral Lumbar Interbody Fusion with Percutaneous Pedicle Screw Fixation Utilizing O-arm Navigation

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Running head: Single-Position XLIF & PPSF Utilizing O-Arm Navigation

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## Abstract

**Objective** Extreme lateral interbody fusion (XLIF) provides indirect decompression of the spinal canal and nerve root foramen while preserving the vertebral structures. Intraoperative guidance during conventional XLIF with percutaneous pedicle screw fixation (PPSF) relies primarily on fluoroscopy, which can expose both surgical staff and the patient to radiation. The use of O-arm navigation during XLIF and PPSF is anticipated to improve accuracy and significantly reduce the risk of radiation.

**Methods** Thirty-one XLIF and PPSF procedures were performed using O-arm navigation in a semi-lateral, single-position setup, including 23 single-level and eight two-level cases. Pathologies included 22 lumbar degenerative spondylolisthesis, seven canal stenosis, and two spondylolytic spondylolisthesis. The control group included 29 patients who underwent two-position XLIF with C-arm fluoroscopy. For each patient, we collated key parameters, including operative time, blood loss, JOA score, ODI, and radiation exposure/doses. Patients were placed in a semi-lateral position. PPSF was first performed under O-arm guidance; subsequently, disc preparation and cage insertion were navigation-assisted and verified by C-arm fluoroscopy.

**Results** Operative time and blood loss were similar between the navigation XLIF and non-navigation XLIF groups. The navigation-XLIF group had a much shorter radiation time (13.01 ± 6.56 *vs.* 66.46 ± 24.62 s) and a lower radiation dose (1.66 ± 0.62 *vs.* 5.48 ± 3.01 mGy). Both groups showed notable postoperative improvements in JOA and ODI scores.

**Conclusion** XLIF with O-arm navigation demonstrated practicality, reliability, accuracy, precise cage placement, and complication rates comparable to those of traditional methods. Enhanced anatomical visualization reduced radiation exposure among surgical personnel.

**Keywords** Extreme lateral interbody fusion, O-arm navigation, Percutaneous pedicle screw fixation, Radiation dose, Radiation exposure, Single-position surgery

## Introduction

Extreme lateral interbody fusion (XLIF), also referred to as direct lateral interbody fusion (DLIF), is a form of lateral lumbar interbody fusion (LLIF) performed *via* a retroperitoneal approach through the psoas major muscle [16, 19]. This technique is used to treat a number of degenerative lumbar conditions, including degenerative spondylolisthesis, degenerative disc disease, and adult spinal deformity [16]. The procedure involves inserting a cage over the annular epiphysis, thereby allowing rapid expansion of the intervertebral spaces and restoration of disc height. Indirect decompression is achieved by ligamentotaxis, which utilizes the surrounding ligaments and spinal canal structures. Minimally invasive XLIF generally requires minimal bone removal and aims to preserves adjacent supporting tissues. Predictive factors for successful indirect decompression include severe canal stenosis, disc collapse, low body mass index (BMI), and spondylolisthesis [28]. However, complications such as lumbar nerve plexus injury, gastrointestinal injury, and vascular damage have been reported [25,28,29].

Over recent years, spinal navigation techniques have advanced rapidly and have been widely adopted for the surgical treatment of degenerative spinal diseases. These techniques can effectively reduce intraoperative radiation exposure and operative time [11, 18]. The utilization of this ,form of navigation, particularly three-dimensional (3D) navigation with an O-arm (Medtronic, Minneapolis, Minnesota, U.S.A.) during oblique lateral interbody fusion (OLIF), a type of anterior psoas approach used in LLIF, enables safer procedures, such as accessing the lumbar intervertebral space, the placement of cages, and the insertion of pedicle screws, while also minimizing exposure to radiation [7, 14, 20, 31]. Currently, intraoperative fluoroscopy is the standard guidance technique for XLIF procedures. However, only one published report has addressed the application of 3D navigation with cone-beam CT in XLIF [24], and no studies to date have investigated the use of O-arm navigation in XLIF.

In the present report, we summarize the outcomes of single-position XLIF procedures and percutaneous pedicle screw fixation (PPSF) performed in the lateral decubitus position using intraoperative O-arm navigation. Clinical results were compared with those obtained from traditional X-ray fluoroscopy-guided XLIF procedures.

## Materials and Methods

Between October 2023 and October 2025, 31 cases underwent single-position semi-lateral O-arm-navigated XLIF and PPSF. Among these, 23 cases involved surgery at a single level and eight involved surgery at two levels. The XLIF approach was adopted in 26 cases, including five using the Crestline method (Nuvasive, Inc., San Diego, California, U.S.A.). Thirty cases involved levels L4-5, whereas 9 involved levels L3-4. The underlying conditions included lumbar degenerative spondylolisthesis in 22 patients, lumbar canal stenosis in seven patients, and lumbar spondylolytic spondylolisthesis in two patients. Mean patient age was 65.93 ± 12.81 years, comprising 12 males and 19 females. Postoperative outcomes were assessed using the JOA score and the ODI preoperatively and postoperatively. Operative time, complications, C-arm irradiation exposure time and dose, and estimated blood loss were retrospectively evaluated. As controls, C-arm fluoroscopy-guided XLIF and O-arm-navigated PPSF were performed on 29 cases during two-position surgeries conducted between November 2022 and October 2025. In the group that underwent XLIF without navigation, 11 patients underwent surgery at two spinal levels, whereas 18 underwent surgery at a single level. The mean age of these participants was 69.55 ± 9.78 years, comprising 15 males and 14 females. Diagnoses included 16 cases of lumbar spondylolisthesis, 12 cases of lumbar canal stenosis, and one case of lumbar spondylolytic spondylolisthesis. Except for one Crestline case, the XLIF approach was utilized for 28 procedures (Table 1).

### Single-position semi-lateral XLIF and PPSF supported by O-arm navigation

While conventional XLIF and PPSF procedures primarily rely on intraoperative X-ray fluoroscopy for guidance, the present study utilized the O-arm system in combination with the StealthStation S8 navigation system (Medtronic, Minneapolis, Minnesota, U.S.A.) for both single-position XLIF and PPSF.

The patient was placed in a semi-lateral decubitus position, angled 30–45° towards the ventral side, with the right side preferred. In addition, the patient was positioned to the right of the operating table to facilitate access for the right-sided insertion of pedicle screws. The patient was securely fastened to the operating table using tape and a reference frame was affixed to the spinous process of the fourth lumbar vertebra and precisely identified under radioscopic guidance. The frame was secured, and the O-arm system was activated. During operation of the O-arm, all surgical staff, except for the radiographer, were asked to exit the operating room. First, PPSF was performed. The skin incision was designed to be 2 cm long at each site, starting from the virtual tip projecting onto the pedicles of the L4 and L5 (or L3) vertebrae. A pilot hole was made in the L4 and L5 (or L3) pedicles (Fig. 1a, b), and a non-cannulated pedicle screw was inserted into the pilot hole under direct

navigation guidance without the use of a guidewire (Fig. 1c, d). The rod was inserted according to the XLIF procedure which was performed *via* a ventral approach. In addition, an operative microscope was used within the intervertebral disc space during the procedure (Fig. 2d). Information sharing among the surgical team was facilitated through an intraoperative monitor, providing educational value.

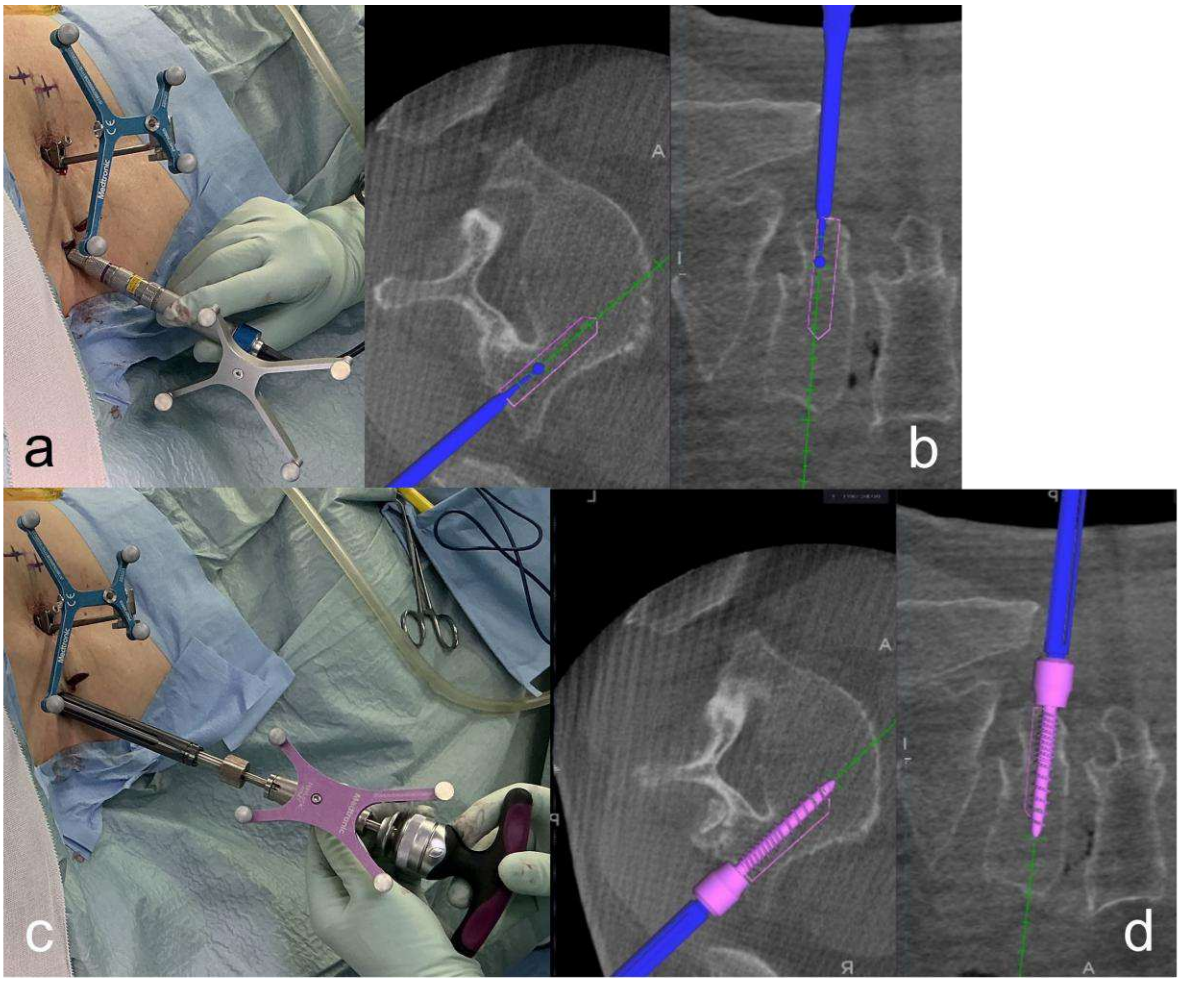



**Fig. 1** O-arm-assisted percutaneous pedicle screw placement was performed in the semi-lateral position prior to extreme lateral interbody fusion (XLIF). (a) a pilot hole for the right L5 pedicle screw was created using the Stealth-Midas system with the patient in right lateral decubitus, shown in cross-sectional and sagittal navigation images (b). (c) a pedicle screw was inserted into the pilot hole, with corresponding L5 cross-sectional and sagittal views (d).

An incision approximately 5 cm in length was generated by delineating the ventral and dorsal margins at the L4-5 or L3-4 level within the left abdomen at the virtual tip. The initial dilator was equipped with the SureTrak device (Medtronic, Minneapolis, Minnesota, U.S.A.), thus facilitating integration with the navigation system (Fig. 2a). While performing nerve monitoring (NVM5 Neuromonitoring system, Nuvasive, Inc., San Diego, California, U.S.A.), the first dilator was advanced to the posterior quadrant of the annulus ring adjacent to the target level *via* the psoas major muscle, confirming that no nearby nerves were present (Fig. 2b). At this stage, a guidewire was placed in the L4-5 or L3-4 intervertebral disc space close to the designated level. Subsequently, the SureTrak device was withdrawn, and the second and third dilators, followed by the MaXcess retractor (Nuvasive, Inc., San Diego, California, U.S.A.), were introduced sequentially and positioned as required (Fig. 2c). Conventionally, retractor docking involves substantial radiation exposure to the surgeon's hand during X-ray fluoroscopy. In contrast, O-arm navigation eliminates time constraints, thus facilitating the procedure while minimizing radiation exposure. The absence of a proximal nerve on the ventral side of the central blade alongside the ball electrode was confirmed. Subsequently, the guidewire insertion point was identified as the intervertebral disc space for shim placement. In addition, the apex of the fibrous ring, once fully exposed and developed, was verified to be positioned at the center of the open wound using the navigated pointer (Fig. 2d, e).

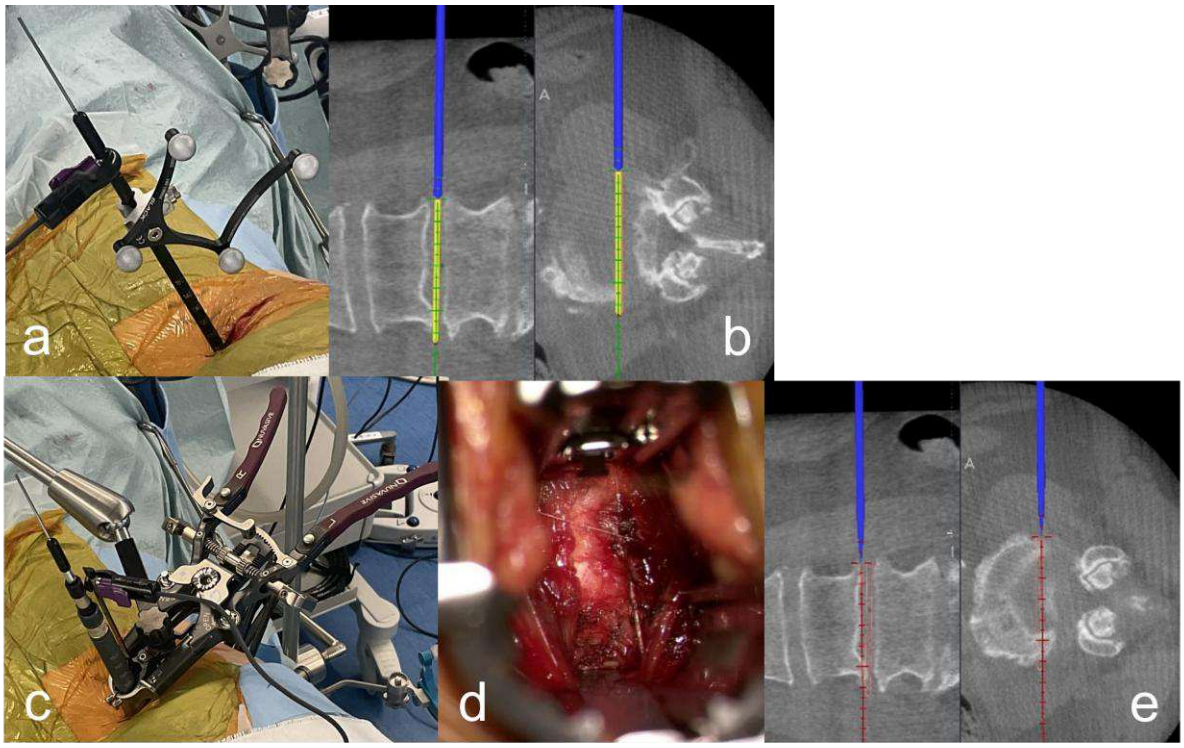



**Fig. 2.** The initial dilator and guidewire, equipped with SureTrak (a), were guided through the psoas major muscle to access approximately one-quarter of the L4-5 annulus ring (b). Continuous nerve monitoring was maintained throughout this process. Following removal of the SureTrak, the second and third dilators, along with the MaXcess retractor (c), were introduced to ensure adequate exposure of the L4-5 disc surface for subsequent procedures (d). The anterior end of the central blade was then identified using a navigated pointer, thereby confirming optimal positioning of the retractor (e).

Discectomy was performed using navigated disc forceps, shavers, ring curettes, and Cobb elevators, all equipped with Navlock (Medtronic, Minneapolis, Minnesota, U.S.A) in accordance with the OLIF protocol. The final trial and cage placement (Fig. 3a, b) were accomplished with O-arm navigation and checked with X-ray fluoroscopy to confirm appropriate bilateral engagement with the annular epiphysis and correct cage thickness (Fig. 3c). Subsequently, a rod with appropriate dimensions was positioned between the pedicle screws and secured, thereby completing the PPSF procedure (Fig. 3d).

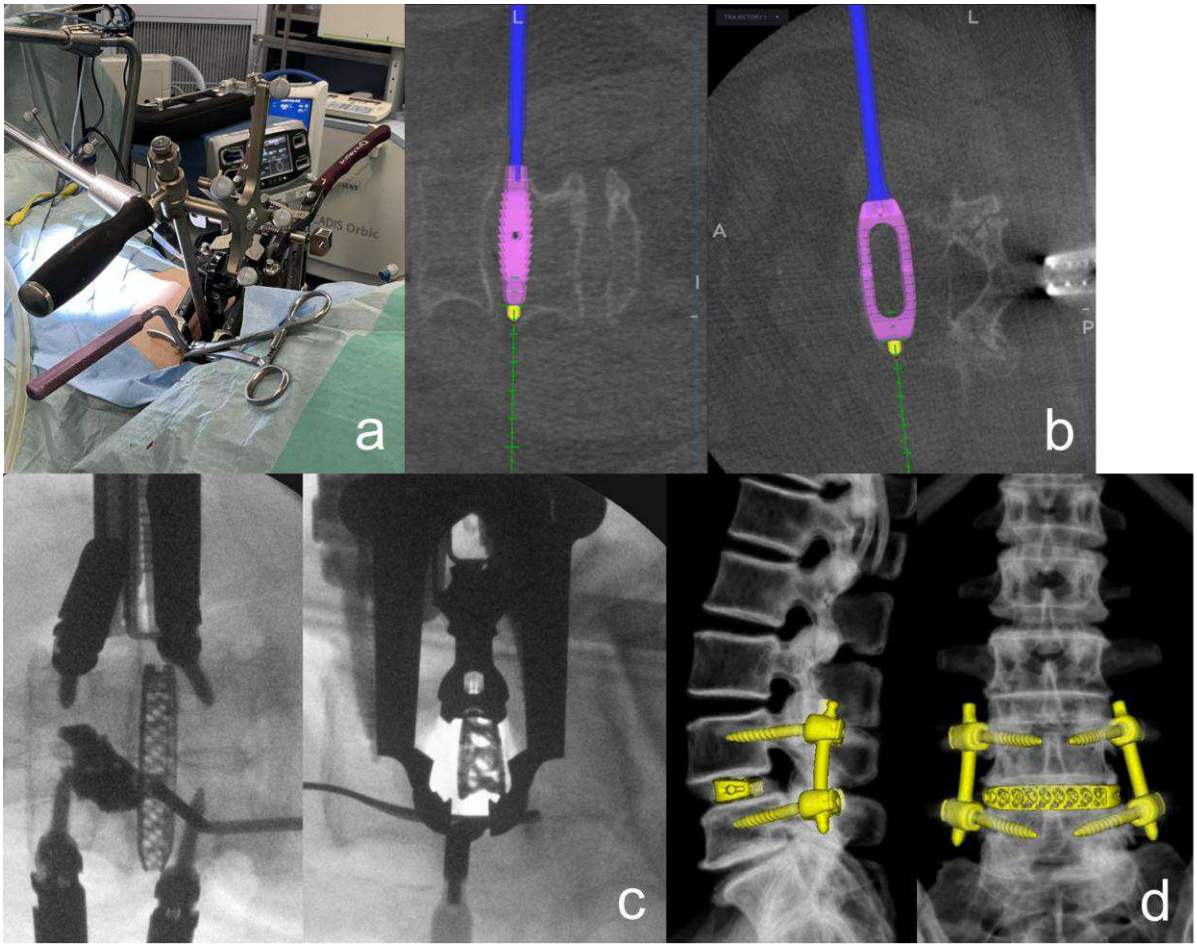



**Fig. 3.** An intraoperative photograph showing the cage inserter being positioned using navigation (a). Navigation images were used to guide the cage insertion (b). X-ray fluoroscopy was used to confirm the correct positioning of the cage (c). Final 3 dimensional-computed tomography images after L4-5 XLIF & percutaneous pedicle screw fixation procedures (d).

### Single-position semi-lateral Crestline and PPSF supported by O-arm navigation

When the iliac crest was high, the XLIF retractor was inserted at an oblique angle under real-time C-arm fluoroscopic guidance to reach the target intervertebral disc space. This type of access is typically achieved by anchoring with a shim and using angled instruments. Alternatively, the Crestline system may be employed *via* an anterior approach to the iliac crest, especially when constraints on XLIF instrumentation under O-arm navigation limit its use. In cases presenting with a prominent iliac crest, the MaXcess retractor was positioned in a reverse anteroposterior orientation, inserted from the ventral aspect of the iliac crest, and affixed to the vertebral bodies at the anterior border of the psoas major muscle. During the procedure, and following trial placement within the intervertebral disc space, the cage was inserted diagonally, consistent with the OLIF technique, and subsequently repositioned vertically during the final placement into the disc cavity (Fig. 4).




**Fig. 4.** Crestline utilized the MaXcess retractor in an anteroposterior reverse orientation to insert the final cage. The cage inserter was initially placed at an angle and subsequently repositioned to ensure perpendicular alignment during the procedure.

### Decubitus XLIF under C-arm fluoroscopy and prone PPSF supported by O-arm navigation

Subjects in the XLIF group were treated with C-arm fluoroscopy and positioned in the right lateral decubitus position. The procedure was conducted in a manner that was similar to the navigated XLIF approach. For PPSF, the patient was positioned prone, a reference frame was attached to the L4 spinous process, an O-arm was used, and the PPSF was performed under navigation.

### Statistical Analysis

Statistical analyses were performed using NCSS 2025 (NCSS, LLC, Kaysville, Utah, USA). Statistical significance was set at $p < 0.05$. Data are presented as mean ± standard deviation or frequency, as appropriate. Group differences were assessed using the independent sample t-test, chi-squared test, and the Mann-Whitney U-test, where applicable.

## Results

Table 1 summarizes the patient demographics and perioperative data. In the present study, 23 single-level procedures were performed using the XLIF technique with O-arm navigation and PPSF and eight were two-level procedures. The mean operative time for the navigation-assisted XLIF group was 172.43 ± 35.50 minutes, compared to 186.62 ± 44.49 minutes in the non-navigation XLIF group. Mean operative blood loss was 17.17 ± 12.19 ml for the navigation-XLIF group and 26.07 ± 29.27 ml for the non-navigation group. These differences were not statistically significant. Although single-level procedures that do not require intraoperative positional changes typically have shorter operative times, the operative time may decrease with increasing experience and progression along the learning curve. The mean duration of X-ray fluoroscopy was 13.01 ± 6.56 seconds for the navigation XLIF group (n=25) and 66.46 ± 24.62 seconds for the non-navigation-XLIF group (n=26), with a significant reduction observed in the navigation-XLIF group ($p<0.001$). Furthermore, the mean radiation dose in the navigation-XLIF group (n=25) was 1.66 ± 0.62 mGy, compared with 5.48 ± 3.01 mGy in the non-navigation-XLIF group (n=26), indicating that navigation-XLIF led to a significant reduction in radiation exposure ($p<0.001$). With the integration of O-arm imaging into standard XLIF procedures, C-arm fluoroscopy is limited to the essential scene, thereby substantially reducing irradiation time and exposure dose. This advancement helps minimize radiation exposure to the operating staff. Postoperative discomfort was noted, including transient difficulty elevating the left thigh by approximately 10%. Temporary numbness of the anterior thigh was observed, which resolved within 1 week. No permanent neurological deficits were identified, and no major complications such as gastrointestinal tract injuries or vascular disorders occurred. We did not observe any malposition or sinking of the pedicle screw and spacer in the present study.

**Table 1** Patient demographics and perioperative data

| Characteristic | Navigation (n=31) | Non-navigation (n=29) | *p*-value |
|---|---|---|---|
| Sex | | | |
| Male | 12 | 15 | |
| Female | 19 | 14 | |
| Age (years) | 65.93 ± 12.81 | 69.55 ± 9.78 | 0.554 |
| Body mass index (kg/m$^2$) | 22.88 ± 2.96 | 23.83 ± 2.60 | 0.340 |
| Types of lumbar degenerative disease | | | |
| Degenerative spondylolisthesis | 22 | 16 | |
| Canal stenosis | 7 | 12 | |
| Spondylolytic spondylolisthesis | 2 | 1 | |
| No. of surgical level | | | |
| 1 | 23 | 18 | |
| 2 | 8 | 11 | |
| Surgical level | | | |
| L3-4 | 9 | 13 | |
| L4-5 | 30 | 27 | |
| Surgical approach | | | |
| XLIF | 26 | 28 | |
| Crestline® | 5 | 1 | |
| Operation time(minute) | | | |
| 1 level | 159.17 ± 22.80 | 165 ± 35.02 | 0.802 |
| 2 level | 216 ± 35.50 | 222 ± 35.21 | 0.610 |
| 1+2 levels | 172.43 ± 35.50 | 186.62 ± 44.49 | 0.171 |
| Estimated blood loss (ml) | 17.17 ± 12.19 | 26.07 ± 29.27 | 0.681 |
| Major complications | 0 | 0 | |
| Radiation exposure time (second) | | | |
| 1 level | 10.80 ± 6.09 (n=18) | 59.35 ± 24.86 (n=17) | <0.001 |
| 2 level | 18.71 ± 3.77 (n=7) | 79.89 ± 18.65 (n=9) | <0.001 |
| 1+2 levels | 13.01 ± 6.56 (n=25) | 66.46 ± 24.62 (n=26) | <0.001 |
| Radiation dose (mGy) | | | |
| 1 level | 1.57 ± 0.70 (n=18) | 4.67 ± 2.93 (n=17) | <0.001 |
| 2 level | 1.90 ± 0.26 (n=7) | 7.02 ± 2.67 (n=9) | <0.001 |
| 1+2 levels | 1.66 ± 0.62 (n=25) | 5.48 ± 3.01 (n=26) | <0.001 |

Values are presented as number or mean±standard deviation

*Crestline* Nuvasive, Inc., San Diego, California, U.S.A.

Table 2 summarizes the comparison of clinical outcomes between the O-arm navigation and non-navigation groups. The mean follow-up duration was 16.83 ± 8.37 months across 30 cases. Significant

postoperative improvements were recorded in terms of JOA and ODI scores: 18.24 ± 4.13 and 13.81 ± 5.92 at 3 months post-operation and 22.59 ± 4.55 and 6.70 ± 3.24 at 1 year, with a mean preoperative score of 8.51 ± 3.36 and 68 ± 8.9, respectively, based on 16 cases monitored for over 1 year ($p<0.05$). The mean follow-up period was 13.10 ± 10.03 months for the non-navigation XLIF group. Statistically significant improvements were observed at 1 year postoperatively: JOA improved from 9.00 ± 3.15 preoperatively to 23.33 ± 4.28, while ODI improved from 69.45 ± 9.12 preoperatively to 7.17 ± 3.12 ($p<0.05$). No statistically significant differences were identified between the navigation and non-navigation XLIF groups. The postoperative outcomes of single-position O-arm-navigated XLIF and PPSF were comparable to those of previous X-ray fluoroscopy-guided XLIF procedures. Furthermore, there was no significant difference in the 12-month bone union rate when compared between the two groups (96.55% *vs.* 96.3%).

**Table 2** Comparison of clinical outcomes between the navigation and non-navigation groups

| Characteristics | Navigation (n=16) | Non-navigation (n=15) | *p*-value |
|---|---|---|---|
| Follow-up period (month) | 16.83 ± 8.37 | 13.10 ± 10.03 | 0.227 |
| JOA score | | | |
| Preoperative | 8.51 ± 3.36 | 9.00 ± 3.15 | 0.462 |
| 3 months | 18.24 ± 4.13 | 19.19 ± 4.93 | 0.390 |
| 12 months | 22.59 ± 4.55 | 23.33 ± 4.28 | 0.564 |
| ODI score | | | |
| Preoperative | 68.00 ± 8.90 | 69.45 ± 9.12 | 0.534 |
| 3 months | 13.81 ± 5.92 | 14.79 ± 6.35 | 0.914 |
| 12 months | 6.70 ± 3.24 | 7.17 ± 3.12 | 0.577 |
| Fusion rate (%) postop. 12 months | 96.67 | 96.55 | 1 |

Values are presented as number or mean±standard deviation
*JOA* Japanese Orthopaedic Association, *ODI* Oswestry Disability Index

## Discussion

The advent and advancement of navigation technology have exerted significant impact on spinal cord surgery [23]. Computer-assisted three-dimensional (3D) navigation offers high-resolution images and detailed views of the vertebral pedicle, thereby enhancing the accuracy of screw placement. In this study, both the navigation and non-navigation groups employed O-arm navigation for the insertion of pedicle screws without misplacement. This technique reduces the risks of nerve injury and clinical complications [30]. Our analyses demonstrated that single-position semi-lateral XLIF performed with O-arm navigation and PPSF can be accomplished with the patient lying on one side. This method demonstrated safety and accuracy comparable to the traditional X-ray fluoroscopy-guided approach, with no significant differences in terms of safety or technique. In the context of 3D-computed tomography (CT)-guided navigation for DLIF procedures, the introduction of O-arm technology by Drazin et al [2]. represented a significant advancement. In their report, they noted that O-arm technology reduced radiation exposure to surgeons and operative staff but also highlighted challenges associated with severe spinal degenerative disease. However, these authors did not report actual cases and complications, detailed imaging outcomes, or the integration of PPSF with O-arm navigation. Park [17] and Joseph et al. [5] reported a minimum 30-day follow-up for 31 OLIF procedures performed with the O-arm system, with operations typically involving 2.1–2.8 levels. These findings indicate that multi-level applications are feasible, with cages correctly positioned in 97% of cases. In another study, Liu et al [10]. reported 63 cases in which OLIF was performed at 117 spinal levels with at least 30 days of follow-up, and the cage was positioned in appropriate area in 98.3% of cases, with an average of 1.9 levels. The single-position OLIF method eliminates the need for redraping, repositioning, intraoperative registration, or the acquisition of CT images. Recent studies increasingly recognize this approach as a practical clinical option that can potentially reduce operative time [1, 13, 15, 22]. Total operative time in the O-arm navigation group has been reported to be shorter than that in a free-hand group [6, 9, 26]. Furthermore, operative times for navigation procedures are known to markedly decrease as learning curves improve [3]. In the present study, there was no significant difference in operative time between the navigation-XLIF and non-navigation-XLIF groups. This may be partially attributable to the ability to perform retractor docking under O-arm navigation without concern regarding the time constraints associated with reduced radiation exposure, which is necessary under C-arm fluoroscopy. Compared to conventional OLIF, single-position OLIF has been reported to reduce operative time and blood loss; however, numerous reports indicate that surgical outcomes and complication rates do not differ significantly between these two techniques [1, 8, 15, 13, 22]. One report described certain complications associated with PPSF in the lateral position [13]; however, several other authors did not observe such differences [1, 15]. The use of O-arm

navigation in PPSF is generally considered to address these concerns effectively. However, extending the application of O-arm navigation to LLIF other than OLIF remains challenging. Currently, navigation devices are incompatible across different manufacturers. Consequently, the widespread adoption of this technique is difficult. In cases involving a high iliac crest, XLIF is generally feasible with the use of angled instruments. However, due to the unavailability of such instruments through 3D-CT navigation, an iliac crest ventral approach comparable to OLIF is normally selected.

In the present study, 3D-CT navigation facilitated anterior operative access, and the procedure was performed through the psoas major muscle using the crestline technique for cases with a high iliac crest. XLIF intervertebral disc procedures for XLIF are typically performed using C-arm fluoroscopy. Accurate positioning of the disc space is possible with SureTrak and O-arm navigation. Using instruments such as disc forceps, ring curettes, or specialized XLIF trials with SureTrak can ensure the precise localization of the intervertebral disc space throughout surgery. In the present study, trials and spacers that had been designed solely for OLIF were used for specific sequences. If these devices cannot be used during O-arm navigation, the virtual tip is substituted with a columnar structure, thus enabling the precise assessment of direction and depth. Hirakawa et al [4]. described the need to rely exclusively on navigated pointers. However, it is difficult to accurately capture the rotational state of the trial and spacer at the virtual tip of the column shape. Therefore, final confirmation during placement must be performed using C-arm fluoroscopy. To address this challenge, we developed a proprietary solution integrated into an inserter designed for XLIF (Fig. 3A, B, 4).

X-ray fluoroscopy is widely used in various minimally invasive surgical procedures; however, the radiation exposure associated with this imaging technique presents potential health risks to both patients and medical staff. This concern is particularly expressed by experienced practitioners who are frequently exposed to radiation during such procedures. Because the operative image of the intervertebral disc space under 3D-CT navigation represents only conceptual visualization, C-arm fluoroscopy was used intraoperatively to determine the cage size by trial insertion and to confirm the final placement. However, radiation exposure was significantly lower than that reported for previous methods. We found that the mean radiation dose decreased from 5.48 mGy to 1.66 mGy, with irradiation times averaging 66.46 seconds for the non-navigation group and 13.01 seconds for the navigation group during XLIF and PPSF procedures involving one or two intervertebral disc levels. According to Villard et al [27]. surgeons in an X-ray fluoroscopy group experienced radiation exposure that was 9.96-fold higher than that in the navigation group. In another study, Liu et al [10]. reported a mean fluoroscopy time of 11.7 seconds per level across 18 eligible cases; all procedures were performed primarily using navigated instruments, with fluoroscopy used only when confirmation of navigational accuracy was required. A recent report indicated that O-arm navigation is both safe and effective for OLIF procedures [20]. Zhang et al. [31] demonstrated a reduction in patient and surgeon radiation exposure during OLIF by comparing 22 cases with CT navigation to 20 cases with conventional fluoroscopy. In another study, Urakawa et al. [24] described the first reported use of XLIF with CT-based navigation using a platform other than the O-arm system. Compared with procedures relying solely on fluoroscopy, these authors reported that the 3D-CT navigation group demonstrated improved perioperative outcomes and accuracy and reduced radiation exposure during cage placement. These findings are particularly encouraging for surgeons without access to the O-arm system. During retractor docking in XLIF surgery, the operator’s hand is at an increased risk of direct radiation exposure, highlighting the need for effective radiation reduction strategies. However, some drawbacks have also been reported. Notably, a multicenter study reported that the use of the O-arm for CT navigation during surgery resulted in higher radiation doses to patients than the C-arm [12], with the mean patient dose in the O-arm group being up to four-fold higher than that in the C-arm group [21]. Furthermore, O-arm navigated LLIF procedures are costly, raising financial concerns.

## Limitations

This study has several limitations that need to be considered. Data were collected from operations in both groups, and clinical outcomes were analyzed retrospectively. First, the sample size was small; therefore, selection bias cannot be excluded. Future research should include large-scale, randomized and controlled trials with extended follow-up periods. Second, the surgery was performed precisely and efficiently by an experienced surgeon at a single facility. Outcomes depended on the surgeon's skills and relative position along the learning curve. Finally, radiation exposure data were obtained from picture archiving and communication system (PACS) rather than from dosimeter badges worn by the patients or operating room staff; consequently, the exact levels of radiation exposure for patients and staff could not be accurately assessed.

## Conclusion

Currently, intraoperative X-ray fluoroscopy is commonly used to guide LLIF and PPSF. However, single-position semi-lateral XLIF performed using O-arm navigation can be comparable to traditional imaging techniques. The application of 3D-CT navigation with XLIF not only helps to ensure that the cage is placed safely and reduces the risk of surgical complications but also provides better insight into complex anatomy. Moreover, incorporating 3D-CT navigation into the XLIF and PPSF techniques reduces radiation exposure for both surgeons and operating room staff, rendering these methods particularly valuable for mitigating radiation-related health risks.

## Declarations

**Ethics approval and consent to participate** This study was approved by the Institutional Review Board (IRB) of Tokyo General Hospital (approval number: 23-16). All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards conducted in accordance with the principles of the Declaration of Helsinki. Consent to participate has been waived.

**Consent for publication** No applicable.

**Data availability** No datasets were generated or analyzed during the current study.

**Competing interests** The authors declare no competing interests.

**Funding** The authors did not receive any financial support for the research, authorship, and/or publication for this article.

**Author Contributions** Conceptualization, methodology, data collection: YI, RKi, RKa, KK, SN; formal analysis, writing-original draft preparation: YI; writing-review and editing: all authors; Project administration: YI, SW. All authors have read and agreed to the submitted version of the manuscripts.

**Acknowledgements** We are grateful to Ms. Rika Sueyoshi, Mr. Kai Takayanagi, Mr. Yohei Asano, and Mr. Akihiko Ishii for their excellent technical support.

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