

Video Article

Cone Beam Intraoperative Computed Tomography-based Image Guidance for Minimally Invasive Transforaminal Interbody Fusion

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Abstract

Transforaminal lumbar interbody fusion (TLIF) is commonly used for the treatment of spinal stenosis, degenerative disc disease, and spondylolisthesis. Minimally invasive surgery (MIS) approaches have been applied to this technique with an associated decrease in estimated blood loss (EBL), length of hospital stay, and infection rates, while preserving outcomes with traditional open surgery. Previous MIS TLIF techniques involve significant fluoroscopy that subjects the patient, surgeon, and operating room staff to non-trivial levels of radiation exposure, particularly for complex multi-level procedures. We present a technique that utilizes an intraoperative computed tomography (CT) scan to aid in placement of pedicle screws, followed by traditional fluoroscopy for confirmation of cage placement. Patients are positioned in the standard fashion and a reference arc is placed in the posterior superior iliac spine (PSIS) followed by intraoperative CT scan. This allows for image-guidance-based placement of pedicle screws through a one-inch skin incision on each side. Unlike traditional MIS-TLIF that requires significant fluoroscopic imaging during this stage, the operation can now be performed without any additional radiation exposure to the patient or operating room staff. After completion of the facetectomy and discectomy, final TLIF cage placement is confirmed with fluoroscopy. This technique has the potential to decrease operative time and minimize total radiation exposure.

Introduction

The TLIF is one of several options available when considering interbody fusion for degenerative disc disease and spondylolisthesis. The TLIF technique was initially developed in response to complications associated with the more traditional posterior lumbar interbody fusion (PLIF) approach. More specifically, the TLIF minimized retraction of neural elements, thereby reducing the risk of nerve root injury as well as the risk of dural tears, which can lead to persistent cerebrospinal fluid leak. As a unilateral approach, the TLIF technique also affords better preservation of the normal anatomy of the posterior elements¹. The TLIF can be performed either open (O-TLIF) or minimally invasive (MIS-TLIF), and MIS-TLIF has proven to be a versatile and popular treatment for lumbar degenerative disease and spondylolisthesis^{2,3,4}. Compared to the O-TLIF, the MIS-TLIF has been associated with decreased blood loss, shorter hospital stay, and less narcotic use; patient-reported and radiographic outcome measures are also similar between open and MIS approaches, thus suggesting the MIS-TLIF is an equally effective but potentially less morbid procedure^{5,6,7,8,9,10,11}.

However, a frequent limitation of the traditional MIS technique is the heavy reliance on fluoroscopy which exposes the patient, surgeon, and operating room staff to non-trivial radiation doses and fluoroscopy time ranging from 46-147 s¹². More recently, however, the use of intraoperative CT-guided navigation has been studied, with several different systems available and described in the literature including the O-arm/STEALTH, Airo Mobile, and Stryker Spinal Navigation Systems.^{13,14} This type of navigated technique has been shown to result in accurate pedicle screw placement while also minimizing the radiation risk to the surgeon^{15,16,17,18,19}. In this article, we present a novel technique for MIS-TLIF that utilizes image-guidance-based pedicle screw placement followed by cage and rod placement with traditional fluoroscopy. This strategy has the potential to increase the speed and accuracy of the pedicle screw placement while minimizing the radiation exposure to both the patient and operating room staff.

Protocol

All procedures and research activities were performed with institutional review board approval (CHR #17-21909).

1. Pre-operative Preparation

1. Induce general anesthesia in the patient, and position the patient prone on the Jackson table with chest bolster and hip pads.
2. Prep and drape the patient's back in the usual sterile fashion.

2. Surgical Procedure

1. Make a small stab incision using a #15-blade over the PSIS contralateral to the side of the planned TLIF.
2. Place a biopsy needle through the stab incision into the ilium to harvest bone marrow aspirate (**Figure 1A**). Drive the navigation reference frame into the PSIS in a trajectory that places the reference arc inferior and medial, thereby avoiding interference with the standard trajectory of an S1 pedicle screw (**Figure 1B**).
3. Cover the wound with a sterile drape with the reference arc exposed and perform an intraoperative CT scan.
4. Plan pedicle screw trajectories using the navigation system (**Figure 1C**); they are generally 3.5 cm lateral to the midline through a one-inch incision on each side for single level fusion (1.5 inch for two levels, and 1.75 inch for three levels).
5. Use a navigated drill guide and 2-3 mm bit and high-speed drill to cannulate the pedicles and utilize K-wires to mark these trajectories.
6. Place the cannulated pedicle screws with reduction towers over the k-wires on the side opposite the TLIF.
7. Determine the trajectory along the disc space using the first tubular dilator which is oriented using the navigation system (**Figure 1D**). Place additional dilators followed by the TLIF retractor, which is connected to a self-retaining arm mounted to the bed.
8. Confirm the retractor positioning via navigation.
9. Perform the laminotomy, flavectomy, and facetectomy in standard fashion under the microscope.
 1. Use a high-speed drill to perform the laminotomy and facetectomy; if just a laminotomy is desired, avoid drilling into the facet joint in order to preserve the structural integrity of the posterior column.
 2. Ensure that the lateral border of the laminotomy is the medial aspect of the facet joint, while the medial border of the laminotomy should be the medial edge of the lamina. Utilize a Woodson elevator to dissect the ligamentum flavum off the dura. Once this is achieved, use a 2 or 3 mm Kerrison rongeur to remove the ligamentum flavum.

NOTE: Navigation allows for maximal safe decompression without violation of the pedicle (**Figure 1D, E**).
10. If contralateral decompression is needed, angle the retractor across the midline and remove the underside of the contralateral lamina, ligamentum flavum, and hypertrophic facet capsule using a 2 or 3 mm Kerrison rongeur.
11. Use the navigation again to identify the trajectory along the disc space to facilitate a safe and thorough discectomy.
12. Prepare the disc space with shavers and distractors.
13. Upon completing the discectomy, use intermittent fluoroscopy to visualize the degree of distraction required during the interbody cage trial placement to ensure preservation of the endplates (**Figure 2A**).
14. Mix the allograft cellular bone matrix with the autologous bone marrow aspirate harvested at the beginning of the operation and carefully pack it into the disc space.
15. Insert the interbody cage (polyetheretherketone [PEEK]), and confirm its position via lateral and antero-posterior (AP) fluoroscopy (**Figure 2B**).
16. Once TLIF has been completed, place the remaining pedicle screws.
17. Carefully drive a pre-bent rod through the screw heads below the dorsal lumbar fascia. Use periodic fluoroscopy to confirm adequate rod length.
18. Gently compress the rods to induce lordosis before securing them with locking set screws.
19. Obtain a final fluoroscopy prior to closure.
20. Close the thoracodorsal fascia with an 0 polyglactin 910 suture, close the subcutaneous tissue with 3-0 polyglactin 910, and approximate the skin edges with skin closure strips. Apply a water tight dressing.

3. Post-surgical Care

1. Ambulate patients on postoperative day 1 with a soft lumbar brace, and obtain standing 36-inch X-rays prior to discharge (**Figure 2C**).
2. Prescribe antibiotics (cefazolin at 2 g intravenous at every 8 h) for 24 h.
3. Provide patients a patient-controlled analgesia (PCA) pump with morphine or hydromorphone overnight and ambulate on postoperative day 1.
4. Transition patients to oral pain medications on the first day and discharge on postoperative day 2 - 3 with follow-up in 6 weeks.

Representative Results

Fifty patients underwent surgery with this technique under a single surgeon (AC). The average age was 53 years (range 29-84 years) with 30 women and 20 men. Patients presented with the following pathology: spinal stenosis (n=45), spondylolisthesis (n=29), facet cysts (n=5), degenerative scoliosis (n=3), and cauda equina syndrome (n=1). Symptoms were back and leg pain in 42 cases, back pain alone in 2 cases, and lower extremity radiculopathy in 6 cases. In 10 cases, patients had undergone previous surgery at the level of pathology. Results are summarized in **Table 1**.

A left-sided approach was used in 25 cases and right-sided in 25 cases. There were 33 single level fusions, 15 two level fusions, and 2 three level fusions. Fusion levels were as follows: L4-5 (n=35), L5-S1 (n=27), L3-4 (n=7), and L2-3 (n=2). The average cage height was 10.2 mm. The mean operative time was 240 min and the average EBL was 80 mL. There was a significant difference in operative time when comparing the number of levels fused; 200 min for single level, 306 min for two levels, and 393 min for three levels ($p<0.001$). The average radiation dose was 62.0 mGy, with 35.3 mGy from the intraoperative CT scan and 26.2 mGy from fluoroscopy. The average duration of fluoroscopy was 42.2 s, with 5.2 s from intraoperative CT scan and 37.1 s from traditional fluoroscopy. The average length of stay after surgery was 3 days (range 1-7 days). The results are summarized in **Table 2**.

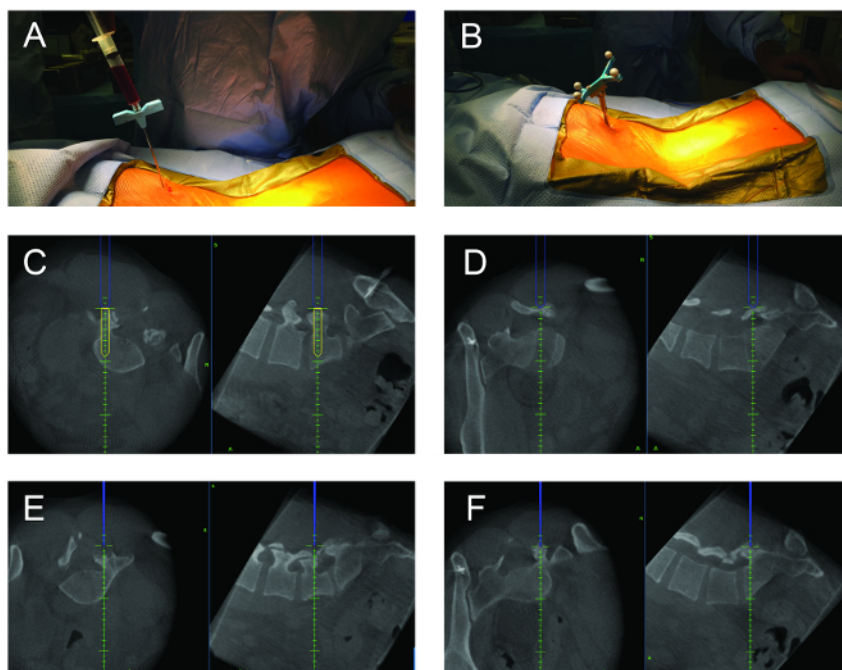


Figure 1. CT-based navigation for MIS-TLIF. A bone marrow biopsy needle is placed through a stab incision into the ilium to harvest bone marrow aspirate (A). The navigation reference frame is placed in the posterior superior iliac spine in a trajectory that places the arc inferior and medial to avoid interference with the standard trajectory of S1 pedicle screws (B). Pedicle screw trajectories are visualized using the navigation system (C). The trajectory along the disc space is determined using the first tubular dilator by navigation (D). The use of intraoperative navigation allows for maximal safe decompression by identifying the location of the superior (E) and inferior (F) pedicles. [Please click here to view a larger version of this figure.](#)

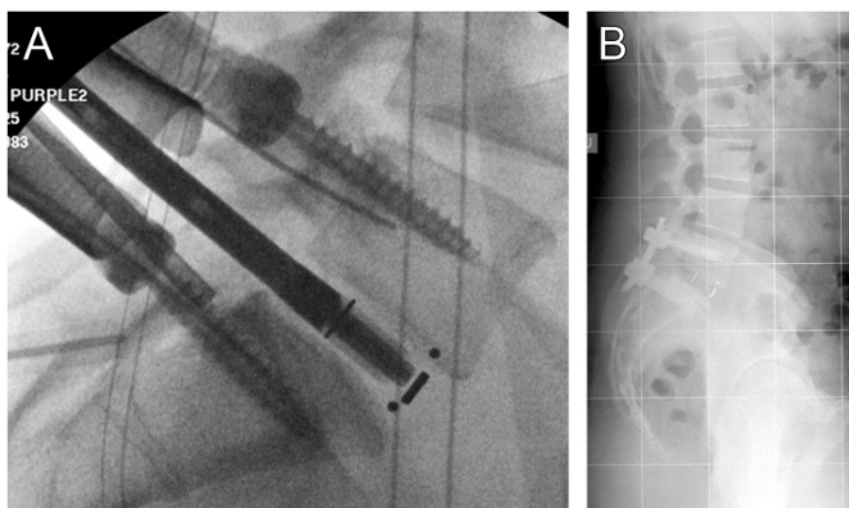


Figure 2. Intraoperative fluoroscopy for interbody cage placement. Fluoroscopy is used during the endplate preparation and distraction to ensure the appropriate height restoration and to avoid violation of the endplates (A). Imaging is used to confirm the appropriate final position (B). Standing 36-inch X-rays (lumbar region shown) are obtained on all patients prior to discharge (C). [Please click here to view a larger version of this figure.](#)

Variable	N=50
Age	
Mean (range)	53 (29-84)
Gender	
Male	20 (40%)
Female	30 (60%)
BMI	
Mean (range)	30 (21-41)
Pathology	
Stenosis	45 (90%)
Spondylolisthesis	29 (58%)
Facet cyst	5 (10%)
Scoliosis	3 (6%)
Cauda equina	1 (2%)
Symptom location	
Back	2 (4%)
Leg	6 (12%)
Both	42 (84%)
Previous surgery	10 (20%)

Table 1. Patient demographics.

Variable	N=50
Approach	
Left	25 (50%)
Right	25 (50%)
Number of levels fused	
One	33 (66%)
Two	15 (30%)
Three	2 (4%)
Levels fused	
L2/3	2
L3/4	7
L4/5	35
L5/S1*	27
Cage height (mm)	10.2 (7-14)
Estimated blood loss (ml)	80 (10-550)
Operative time (min)	240 (88-412)
Radiation dose (mGy)	
Intraoperative CT	35.3 (21.5-68.7)
Fluoroscopy	26.5 (4.3-64.3)
Total	62.0 (28.9-120.7)
Radiation exposure (sec)	
Intraoperative CT	5.2 (1.0-24.5)
Fluoroscopy	37.1 (8.7-94.6)
Total	42.2 (12.2-100.0)
Length of stay (days)	3.1 (1-7)
* One patient with L5/L6 interbody fusion	

Table 2. Surgical characteristics.

Discussion

There are several critical steps to the procedure described. The first critical step is the process of registration. The reference arc must be placed in solid bone and should be oriented appropriately to avoid interfering with the S1 pedicle screw placement if needed. The second critical step is maintaining accuracy of the navigation after an intraoperative CT scan is performed, which can be done by identifying normal anatomic structures and confirming the correct positioning. The accuracy should be periodically verified. Perhaps one of the limitations of the described technique is that the navigation can be inadvertently altered in the middle of an operation. Registration is derived from a fixed patient position on the operating table. As a result, any translational movement of the patient or the reference frame itself can dramatically influence the accuracy of navigation. Great caution must particularly be taken when applying any downward forces (such as during the placement of pedicle screws)²⁰. Nevertheless, if there are any concerns regarding accuracy, the surgeon must not hesitate to repeat the registration to ensure high fidelity of the navigation.

Another critical step is the preparation of the disc endplates for interbody cage placement, as the endplates must not be violated, which can result in cage subsidence. The rates of PEEK cage subsidence in MIS-TLIF can be as high as 15%²¹, thus optimizing the cage fit can dramatically reduce the risk of migration, subsidence, and collapse; the endplate preservation is critical to achieving this goal^{22,23}. Intermittent fluoroscopy can be helpful at this point to visualize the amount of distraction and end plate preservation. Final fluoroscopy can also be performed to confirm satisfactory cage positioning and placement²⁴. In that manner, fluoroscopy remains a critical tool for this technique, particularly during discectomy, distraction, and cage placement. While image-guidance navigation allows for pedicle screw placement, intermittent fluoroscopy provides a "real-time" view to evaluate endplate preservation during discectomy and confirm the appropriate cage trajectory and final placement.

Apart from navigation registration errors, another limitation to the proposed technique is that contemporary navigation protocols do not exist for guidewire navigation. This leads to a theoretical risk of threading the guidewire deep past the vertebral body and causing intraabdominal injury. In order to minimize this risk, we recommend pulling the guidewire back by several inches after cannulating the proximal pedicle²⁰.

There is a general consensus that MIS techniques are associated with increased radiation exposure when compared to traditional open techniques due to their reliance on fluoroscopy²⁵. Developing strategies to reduce radiation exposure and shorten operative time are critical to improving outcomes while minimizing the dangers of radiation overexposure²⁵. Incorporating the intraoperative CT scan for navigation allows for

the placement of pedicle screws without the need for constant fluoroscopy. Villard *et al.* found that radiation exposure using freehand techniques was almost 10 times higher than with navigation-guided techniques in a cohort of patients who underwent standard open posterior lumbar instrumentation²⁶. Tabaree *et al.* demonstrated that the use of the O-arm resulted in similar breach rates as the C-arm, and radiation exposure was lowered for the surgeon but increased for the patient²⁷. In another cadaveric study for iliosacral screw placement, Theologis *et al.* confirmed that the use of the O-arm increases radiation exposure to the patient²⁸.

There are limited data on radiation exposure associated with the technique described in this manuscript; previous studies present radiation exposure as the total fluoroscopy time in seconds, while much of these data are generated from studies comparing traditional open TLIF to MIS-TLIF. Using image-guidance for pedicle screw placement, we found a reduction in the total fluoroscopic time compared to historical studies (42 s compared to 45-105 s). Furthermore, the average radiation dose in our study was 62.0 mGy with intraoperative CT scan accounting for 57% (35.4 mGy) of the radiation exposure; this compares favorably to a study performed by Mendelsohn *et al.*, where intraoperative CT for navigation during spinal instrumentation increased the total radiation dose to the patient by 8.74 times²⁹. However, the reduction in radiation was associated with an increase in operative time given that image acquisition can result in delays related to equipment transport and in some cases the need for multiple rounds of image acquisition. The results of this technique compare favorably to historical studies with respect to EBL and length of stay.

An advantage to our approach is that in certain cases, it eliminates the need for preoperative CT scan since these images can be acquired in the operating room. There are limited data on patient BMI and associated radiation exposure. Larger body habitus often requires increased radiation dosage to penetrate the soft tissue and may require additional exposures as the dosage is optimized intraoperatively. Bivariate correlation statistics found a Pearson correlation of 0.358 between BMI and fluoroscopy dose ($p=0.013$), but a value of 0.003 between BMI and fluoroscopy time ($p=0.983$), confirming that increased radiation dose, not increased time, was correlated with BMI.

This study is limited by its retrospective design. Additionally, there is frequently a high demand for intraoperative CT scan and these machines are not always available, resulting in a "wait time" for this part of the operation. Coordinating intraoperative CT scan availability with the OR start time has the potential to shorten total operative time by decreasing the "wait time." Radiation exposure associated with intraoperative CT scan is relatively fixed, however, fluoroscopy represents an area for further radiation exposure reduction. Use of low dose protocols can be utilized, but their viability in obese patients and multilevel MIS-TLIFs is not yet validated. We are encouraged that even in these preliminary data, the average fluoroscopy time of 41.6 s compares very favorably to historical reports; when considering that our study included two and three level fusions, these data are even more promising. Future studies will incorporate streamlined communication with operating room staff and radiation technologists as well as low-dose fluoroscopy protocols.

In conclusion, in this article, we describe a single-surgeon experience using a novel technique incorporating a mixture of intraoperative CT-guided navigation and traditional fluoroscopy when performing an MIS TLIF. Such a technique represents an intermediary in the transition towards exclusively using navigation in the future^{30,31,32}. One of the potential benefits of this technique is the reduction of radiation exposure to the patient as well as the surgeon. Preliminary results show promise, and future studies may prove further benefits with this technique.

Disclosures

Dr. Aaron Clark is a consultant for Nuvasive. Dr. Pekmezci, Safaee, and Oh have nothing to disclose.

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