Radiation Exposure and Operation Time in Percutaneous Endoscopic Lumbar Discectomy Using Fluoroscopy-Based Navigation System

Hao Qin[1,2], Shengbin Huang[2], Lin Xu[2], Pingou Wei[2], Jianzhong Jiang[2], Zhaolin Xie[2], Xiang Luo[2], Haitao Tan[1,2], Wenhua Huang[1,3]

■ OBJECTIVE: **This study evaluated radiation exposure and operation time of percutaneous endoscopic lumbar discectomy (PELD) by using a fluoroscopy-based navigation system for access and localization.**

■ METHODS: **Eighty-six PELDs performed by a single surgeon were retrospectively analyzed. Patients were separated into 2 groups: group A (using a three-dimensional [3D]-printed navigation instrument and fluoroscopy-based navigation system) and group B (with conventional fluoroscopy and standard instrumentation). The operation, fluoroscopy, and total access time were collected, as well as fluoroscopy and access times.**

■ RESULTS: **The operative time for group A was 59 minutes (standard deviation [SD], 6 minutes) and 106 minutes (SD, 15 minutes) in group B (*P* < 0.001). In group A, fluoroscopy was used an average of 5 times (SD, 0.7) and 29 times (SD, 8) in group B (*P* < 0.001). The fluoroscopy time was 9 minutes (SD, 2 minutes) in group A and 40 minutes (SD, 8 minutes) in group B (*P* < 0.001). The number of access attempts was 1.3 (SD, 0.5) in group A and 8 (SD, 2 times) in group B (*P* < 0.001). The total access time was 11 minutes (SD, 2 minutes) in group A and 28 minutes (SD, 5 minutes) in group B (*P* < 0.001).**

■ CONCLUSIONS: **PELD using the fluoroscopy-based navigation system showed lower operative, fluoroscopy, and access time compared with conventional techniques. In addition, fewer fluoroscopy images and access attempts were made in the navigation group. These data suggest that this novel technique reduces fluoroscopy and operation time and may reduce risks of repeated surgical access attempts.**

INTRODUCTION

Lumbar disc herniation (LDH) is a common degenerative spinal disease that often results in low back and/or radicular pain, which can seriously affect an individual's quality of life and work.[1-3] Nonsurgical treatment options can control some symptoms of LDH, but discectomy is indicated when nonsurgical treatments are intractable.[4,5] Traditional open discectomy can treat various types of LDH; however, it may have many disadvantages such as more paravertebral muscle damage and bleeding, posterior ligamentous and bony structure destruction, nerve root injury during direct manipulation, and chronic neural edema and fibrosis caused by injury to the epidural venous system.[6-8] Percutaneous endoscopic lumbar discectomy (PELD) is an alternative technique with several advantages over conventional approaches for discectomy, such as preservation of paravertebral musculature, ligamentous, and bony structures, low risk of iatrogenic instability and postoperative epidural scar formation, minimal postoperative pain, less blood loss and postoperative pain, and shorter hospital stay.[9,10] Also, the annulus can be

Key words
- 3D printed
- Fluoroscopy
- Navigation
- Operation time
- Percutaneous endoscopic lumbar discectomy

Abbreviations and Acronyms
3D: Three-dimensional
BMI: Body mass index
JOA: Japanese Orthopaedic Association
LDH: Lumbar disc herniation
MRI: Magnetic resonance imaging
ODI: Oswestry Disability Index
PELD: Percutaneous endoscopic lumbar discectomy
SD: Standard deviation
VAS: Visual analog scale

From the [1]Guangxi Medical University, Nanning, Guangxi; [2]Orthopaedic Department, Guigang People's Hospital, Guigang, Guangxi; and [3]Southern Medical University, Guangzhou, Guangdong, China

To whom correspondence should be addressed: Wenhua Huang, M.D. [E-mail: 13822232749@139.com]

Hao Qin, Shengbin Huang, and Lin Xu contributed equally to this work.

Citation: World Neurosurg. (2019) 127:e39-e48.
https://doi.org/10.1016/j.wneu.2019.01.289

Journal homepage: www.journals.elsevier.com/world-neurosurgery

Available online: www.sciencedirect.com

repaired by using radiofrequency technology.[11] PELD is a well-accepted technique in the treatment of patients with LDH.

Safe and accurate preoperative localization of disease is a key step of the procedure and one of the difficulties of PELD over conventional open techniques, because visualization is limited.[12,13] Challenges with identification of the LDH in PELD may also affect the clinical outcome after surgery.[12] Preoperative location is guided by fluoroscopy, which does not provide accurate depth approximations or paracentesis angle for approach instrumentation.[14] When using fluoroscopy in PELD, it is necessary for the surgeon to estimate the incision position and then use spatial orientation along with the surgeon's anatomic and procedural experience to approach the LDH.[15,16] Therefore, PELD poses a technical challenge to surgeons who are building their spatial, anatomic, and procedural knowledge and experience. How this challenge can manifest in these surgeons is repeated use of fluoroscopy during percutaneous development of the working channel into a safe and accurate position, which may increase paravertebral muscle injury and potential radiation exposure for both surgeons and patients and also increase the risk of dural sac and nerve root injury and, in the case of a complication, extend the duration of the learning curve. Percutaneous placement of the working instruments into an ideal position expeditiously is still one of the remaining technical challenges in PELD. In recent years, computer-assisted navigation systems have been used for the placement of lumbar, thoracic, and cervical pedicle screws.[17-20] Multiple clinical studies have shown that the accuracy of these navigation systems for screw placement is superior to that of screws placed under conventional fluoroscopy.[21,22] In this study, a navigation cannula that could be connected to a fluoroscopy-based navigation system was designed and printed out by a metal three-dimensional (3D) printer. Assisted with the 3D-printed navigation cannula, a fluoroscopy-based navigation system was used for access/localization of PELD. The purpose of this study was to evaluate the fluoroscopy-based navigation system for accuracy and surgical efficiency compared with a conventional fluoroscopy method.

METHODS

Design of 3D-Printed Navigation Cannula

In IMAGEWARE V12.1 software (Siemens PLM Software, Plano City, Texas, USA), a navigation cannula was designed, which included a cannulated rod with an internal diameter of 1 mm and a length of 200 mm. The navigation cannula was divided into 2 parts: 1 distal and 1 proximal part. The distal part had an internal diameter of 1 mm, an external diameter of 2.5 mm, a length of 170 mm, and a small tip used for development of a stab incision. The proximal part had an internal diameter of 1 mm, an external diameter of 8 mm, a length of 30 mm, and a handle at the proximal end used for connecting a navigation receiver array (Figure 1A and B). After completion of design, the imaging data were saved in .hbd format and were output to a metal 3D printer (SLM-300 [Hanbang Science and Technology Ltd,

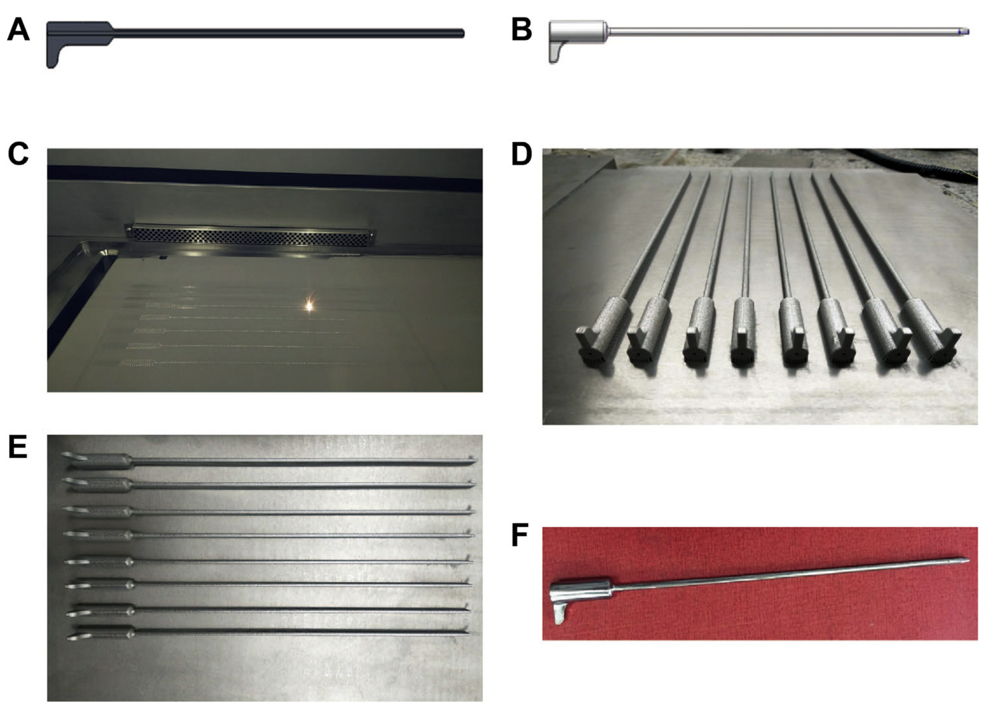

Figure 1. (**A**, **B**) Navigation cannula was designed in IMAGEWARE V12.1 software, (**C**) Three-dimensional (3D) printing navigation cannula was printed in a metal 3D printer. (**D**, **E**) 3D printing navigation cannula was printed out. (**F**) 3D printing navigation cannula after heat treatment, surface finishing.

Guangdong, China]). Using titanium alloy (Ti-6Al-4V) as the printing material, a 3D printing navigation cannula was printed out, which could be used in clinical surgery after heat treatment, surface finishing, and high-temperature sterilization (Figure 1C–F). This 3D-printed navigation cannula was designed in general with different lengths (200 mm, 220 mm, 240 mm, and 260 mm). A 200-mm navigation cannula could be selected for patients with low body mass index (BMI, calculated as weight in kilograms divided by the square of height in meters). According to the patient's BMI, the length of navigation cannula could be selected. For patients with very high BMI, a longer navigation cannula could be designed.

GENERAL INFORMATION

A total of 86 patients with LDH who underwent PELD were retrospectively reviewed from the practice of a single surgeon between January 2015 and October 2017. The study was approved by the local ethical committee of human resources. The diagnosis of LDH was based on patient histories, signs and symptoms, physical examinations, and lumbar magnetic resonance imaging (MRI). Inclusion criteria were: 1) single-level LDH at L3-4, L4-5, or L5-S1, 2) shown by MRI, 3) between 18 and 65 years of age, 4) having undergone unsuccessful nonoperative treatments for at least 6 weeks, and 5) type of disc herniation (central or paracentral). Exclusion criteria included patients 1) who required other spine surgeries, 2) who had multilevel LDH, 3) who had mental illness, 4) who had evidence of cauda equina syndrome, 5) who had chronic calcified disc herniation, 6) or in whom LDH was combined with spinal infection, vertebral fractures, and/or spinal tumor.

The 2 groups were divided randomly according to admission order with the random number table and 86 PELD cases were treated by a single surgeon. Forty-three each were included in group A and group B. Patients who underwent PELD performed by 1 surgeon with a 3D printing navigation cannula and fluoroscopy-based navigation system were assigned to group A, whereas patients who underwent PELD performed by the same surgeon with a conventional fluoroscopy method were assigned to group B.

SURGICAL PROCEDURES

Conventional Technique for Localization and Incision

All patients in group B were placed in the prone position on a radiolucent table under guidance of C-arm fluoroscopy. All procedures were performed under local anesthesia with sedation. During the procedure, the surgeon could communicate with the patient. First, the median line along the spinous process and the iliac crest were marked. The target segment and access point was located using K-wires with repeated C-arm fluoroscopy. According to the typical TESSYS (transforaminal endoscopic spine system) technique, the selection of the entry point was respectively 8–10 cm, 11–14 cm, and 12–16 cm at the L3-L4, L4-L5, and L5-S1 level from the midline of the spinous process.[23,24] The final entry point was variable, which was determined by the specific anatomy and conditions (gender, BMI, and anatomic features) of the patients, at the surgeon's discretion. Repeated fluoroscopy was needed to confirm the incision and the working channel location. The following surgical procedure was the same as the conventional endoscopic discectomy.

Using 3D Printed Navigation Instrument and Fluoroscopy-Based Navigation System for Localization and Incision

All patients in group A were placed in the prone position on a radiolucent table under guidance of C-arm fluoroscopy. All procedures were performed under local anesthesia with sedation. During the procedure, the surgeon could communicate with the patient. The median line along the spinous process and the iliac crest were marked. A 3D navigation cannula and fluoroscopy-based navigation system (Stealth Station S7 navigation system [Medtronic Sofamor Danek, Memphis, Tennessee, USA]) were used in identifying the incision site and working channel location. To begin the navigation registration, the reference frame with 4 infrared light-reflecting diodes was inserted into the posterior superior iliac spine of the contralateral side to the approach through a small incision (Figure 2A). Next, anteroposterior and lateral position images of the lumbar vertebra were obtained, and the images were transferred to the navigation system. Then, the 3D navigation cannula was connected to the navigation adapter (Figure 2B). The accuracy of the 3D-printed navigation cannula was verified by using the navigational pointer on the reference frame (Figure 2C).

Once operational accuracy was confirmed, the 3D navigation cannula was used to make a stab incision, with the selection of the entry point the same as with the typical TESSYS technique (Figure 2D–F). A fluoroscopy-based navigation system was used for access/localization of PELD. Once the ideal location of the navigation cannula was confirmed on the navigation screen, a guide wire was inserted through the navigation cannula (Figure 2G). Then, the 3D navigation cannula was pulled out and a dilator was installed along the guide wire (Figure 2H and I). The working channel was further confirmed by the anteroposterior and lateral position X-ray films of lumbar vertebra (Figure 2J and K). The following procedures were the same as those in conventional endoscopic discectomy.

Postoperative Treatment and Follow-Up

After surgery, all patients were given dexamethasone and mannitol for 1 day and discharged on the second day. Eighty-six patients were followed up at 1 week, 4 weeks, and 3, 6, and 12 months after surgery. Postoperative visual analog scale (VAS), Japanese Orthopaedic Association (JOA), and Oswestry Disability Index (ODI) scores were evaluated and recorded at the last follow-up.

Observational Parameters

Basic patient and treatment information was collected including gender, age, time of conservative therapy, BMI, surgical lumbar segment, and fluoroscopy voltage and current. Primary end points included operative, fluoroscopy, and access/exposure time as well as the number of times that fluoroscopy was used and the number of times that instrumentation had to be repositioned to determine a safe working passage. All these outcomes measures were obtained by a secretary in our department after the patient was placed in the prone position and the median line along the spinous process and the iliac crest were marked. All measures

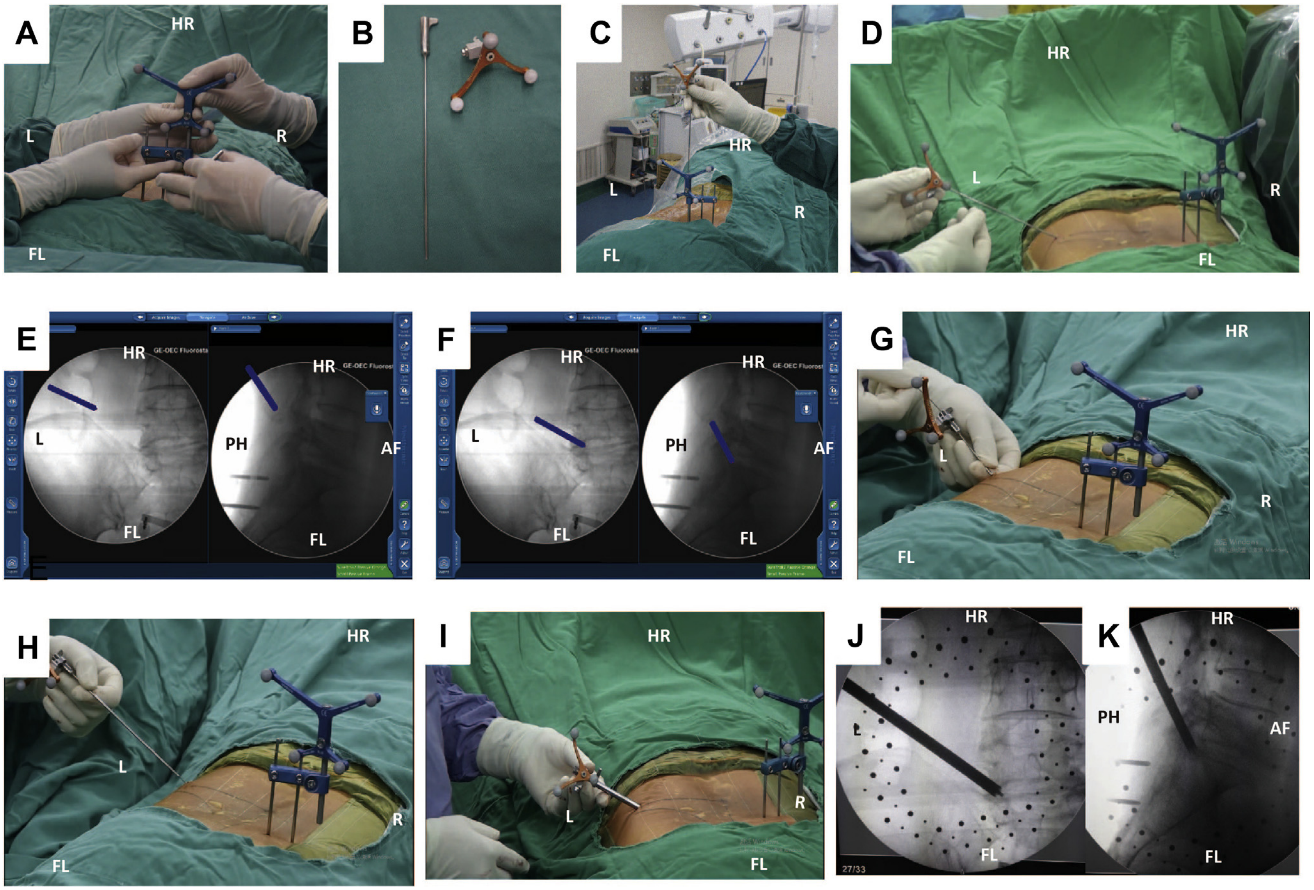

Figure 2. (**A**) Reference frame with 4 infrared light-reflecting diodes was inserted into the posterosuperior iliac spine of the contralateral side. (**B**) Three-dimensional (3D) navigation cannula was connected to the navigation adapter. (**C**) The accuracy of 3D-printed navigation cannula was verified by using the navigational pointer on the reference frame. (**D**–**F**) With the selection of the entry point the same as with the typical TESSYS technique, 3D navigation cannula was used to make a stab incision and access. (**G**) Once the ideal location of navigation cannula was confirmed on the navigation screen, a guide wire was inserted through the navigation cannula. (**H**–**I**) 3D navigation cannula was pulled out and a dilator was installed along the guide wire. (**J**–**K**) The working channel was further confirmed by the anteroposterior and lateral position X-ray films of the lumbar vertebra. HR, head/roof; AF, anterior/front; PH, posterior/hamsprings; FL, foot/leg; L, left; R, right.

were compared between groups A and B. In addition, preoperative and postoperative VAS, JOA, and ODI scores were recorded.

Preoperative and postoperative sagittal and axial MRI views were used to measure canal diameter, obtained and analyzed at a single 3-T MRI scanner (MAGNETOM Verio [Siemens AG, Erlangen, Germany]) before surgery and within 2 weeks after surgery (Figure 3, Supplementary File 1 and 2). A midsagittal slice was used to determine anteroposterior canal diameter (mm). An axial slice through the center of the disc was used to measure central canal area (mm^2). The MRI scanner software (NUMARIS/4 [Siemens AG, Erlangen, Germany]) was used to measure linear dimensions and areas.

Statistical Analyses

All statistical analyses were performed with SPSS version 16.0 (SPPS Inc., Chicago, Illinois, USA). Continuous variables between group A and group B were analyzed with the Student *t* test, whereas categorical variables were analyzed using a χ^2 test. The Pearson correlation test was used to evaluate potential correlations between operative time, fluoroscopy time, access/localization time, number of times fluoroscopy was used, and number of access/localization attempts. Statistical significance was defined at $P < 0.05$.

RESULTS

The characteristics of all 86 patients with LDH treated with PELD are shown in Table 1. Forty-three patients were included in each group. There were 25 men and 18 women in group A and 27 men and 16 women in group B ($P = 0.659$). The average age of patients in group A was 43 years (standard deviation [SD], 7 years) in group A and 41 years (SD, 9 years) in group B ($P = 0.228$). The mean time of conservative therapy was 18 weeks (SD, 11 weeks) in group A and 19 weeks (SD, 11 weeks) in group B ($P = 0.682$). The average BMI was 21.3 kg/m^2 (SD, 1.3 kg/m^2) in group A and 21.3 kg/m^2 (SD, 1.1 kg/m^2) in group B ($P = 0.934$). There were, respectively, 7,

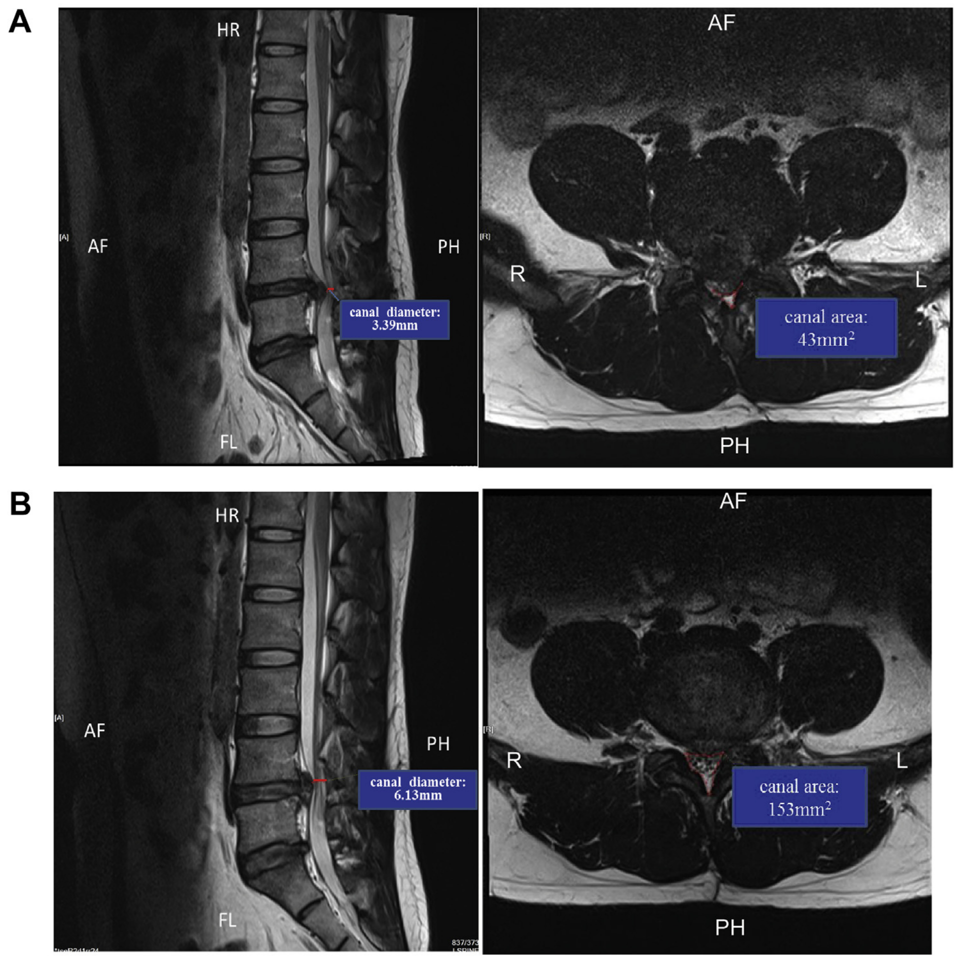

Figure 3. (**A**) Preoperative magnetic resonance imaging views of anteroposterior canal diameter (mm) and central canal area (mm^2). (**B**) Postoperative magnetic resonance imaging views of anteroposterior canal diameter (mm) and central canal area. HR, head/roof; AF, anterior/front; PH, posterior/hamsprings; FL, foot/leg; L, left; R, right.

21, and 15 cases at the L3-4, L4-5, and L5-S1 levels in group A, whereas there were 9, 19, and 15 cases at the L3-4, L4-5, and L5-S1 levels in group B, respectively ($P = 0.839$). There were no significant differences in fluoroscopy voltage and current between the 2 groups ($P > 0.05$).

The mean operative time for patients in group A was 59 minutes (SD, 6 minutes) and 106 minutes (SD, 15 minutes) for those in group B. Patients in group B had a statistically significantly longer mean total operative time than did patients in group A ($P < 0.001$). In group A, fluoroscopy was used an average of 5 times (SD, 0.7) and it was used an average of 29 times (SD, 8) in group B ($P < 0.001$). The fluoroscopy time was 9 minutes (SD, 2 minutes) in group A and 40 minutes (SD, 8 minutes) in group B ($P < 0.001$). The mean number of times that access attempts had to be explored was 1.3 (SD, 0.5) in group A and 8 (SD, 2) in group B ($P < 0.001$). The total access time was 11 minutes (SD, 2 minutes) in group A and 28 minutes (SD, 5 minutes) in group B ($P < 0.001$). There were strong correlations between the number of times that fluoroscopy was used and total fluoroscopy time ($r^2 = 0.986$; $P < 0.001$), the number of times that access attempts were made and access time ($r^2 = 0.924$; $P < 0.001$), fluoroscopy time and access time ($r^2 = 0.932$; $P < 0.001$), the number of times that fluoroscopy was used and the number of access/localization attempts ($r^2 = 0.940$; $P < 0.001$), fluoroscopy time and operative time ($r^2 = 0.963$; $P < 0.001$), access time and operative time ($r^2 = 0.925$; $P < 0.001$) (Table 2, Figure 4).

The preoperative and postoperative back VAS score, leg VAS score, JOA score, and ODI were not significantly different between the 2 groups (all $P > 0.05$). However, within groups, all measures significantly improved from preoperative to postoperative time points ($P < 0.05$) (Table 3).

Table 1. Basic Characteristics of Patients Treated with Percutaneous Endoscopic Lumbar Discectomy

Variables	Group A	Group B	*P* Value
Gender (men/women), n	25/18	27/16	0.659
Age (years)	42.77 ± 7.39	40.86 ± 9.06	0.288
Time of conservative therapy (weeks)	17.72 ± 10.66	18.70 ± 11.35	0.682
Body mass index (kg/m^2)	21.30 ± 1.25	21.32 ± 1.08	0.934
Lumbar segment			0.839
L3-L4	7	9	
L4-L5	21	19	
L5-S1	15	15	
Anteroposterior voltage (kV)	74.71 ± 1.63	74.55 ±1.19	0.608
Anteroposterior current (mA)	4.28 ± 0.21	4.28± 0.25	0.963
Lateral voltage (kV)	3.15 ± 0.44	3.22 ± 0.44	0.478
Lateral current (mA)	2.97 ± 0.39	3.01 ± 0.37	0.651

Dimensional increases of the canal were seen in sagittal and axial MRI views, although there were no statistically significant differences from preoperatively to postoperatively or between the 2 groups ($P > 0.05$). There were 3 patients with herniation recurrence in group A and 2 patients in group B ($P = 1.000$). Most of these recurrent patients were engaged in physical labor early after surgery. All had good outcomes of neurologic recovery and pain relief after reoperation with PELD. Four patients with postoperative disc remnants were identified in group A and 6 patients in group B ($P = 0.776$) (Table 4). In these patients, most remnant fragments were sequestrated disc fragments, and 3 patients with pain remnants needed a second-stage PELD, whereas 7 patients with pain-free remnants received conservative treatments. There were no infections, hematomas, or nerve injuries in either group.

DISCUSSION

PELD, as a minimally invasive technique, is well accepted by surgeons and well tolerated by patients with LDH, with few associated risks and higher long-term success rates than alternative nonoperative techniques.[25,26] However, safe and accurate preoperative disease location is a key step of PELD that may affect the clinical outcome after surgery. Conventional localization methods of PELD rely heavily on the surgeon's experience with the technique and local anatomy, as well as tactile feedback, spatial understanding, repeated fluoroscopy, and access attempts.[27,28] Therefore, these methods may increase radiation exposure to both surgeons and patients. Also, repeated fluoroscopy and exposure attempts may extend the operative time and may increase the risk of paravertebral, dural sac, and nerve root injury.[29,30] In addition, localization of bony landmarks by tactile feedback is not sensitive or reproducible.[23] Limited in spatial understanding and practical/anatomic experience, some surgeons also require repeated attempts using fluoroscopy to place the working channel percutaneously into a safe and accurate location at the beginning phase of learning PELD, which may undermine their confidence and make their learning curve of PELD both steep and long.[23,31] Long-term radiation exposure may be associated with potential diseases such as cataract formation, leukemia, skin erythema, thyroid cancer, and other malignancies.[32-34] Therefore, it is of great importance to reduce the fluoroscopy exposure of surgeons and patients to decrease risk of potential radiation-induced diseases.

Table 2. Procedure-Related Outcomes of Percutaneous Endoscopic Lumbar Discectomy Between Group A and Group B

Variables	Group A	Group B	*P* Value
Operation time (minutes) (SD)	59 (6)	106 (15)	<0.001
Number of fluoro images taken (SD)	5 (0.7)	29 (8)	<0.001
Operation time (minutes) (SD)	9 (2)	40 (8)	<0.001
Number of access attempts (SD)	1.3 (0.5)	8 (2)	<0.001
Operation time (minutes) (SD)	11 (2)	28 (5)	<0.001

SD, standard deviation.

Thus, identification of instrumentation and techniques to minimize localization variance, decrease radiation, and reduce operative time was the focus of the novel techniques presented in this work. Other researchers have studied new localization and exposure methods for PELD in the past few years to improve localization accuracy and reduce radiation and the learning curve of PELD.[23,35] Choi et al.[36] reported their experiences with image-guided PELD using a specially designed fluoroscope with an MRI-equipped operative suite (XMR); their analysis indicated that XMR-assisted PELD could provide a precise skin entry point and confirm that decompression occurs intraoperatively. However, the cost of the procedure and inventories was expensive, and the time that a patient had to stay in the operating room was long. Fan et al.[37,38] used their self-made isocentric navigation, which was a surface locator and navigator-assisted device, to reduce the radiation exposure and operation time of PELD; the navigator-assisted device was just a mechanical structure and the accuracy of access/

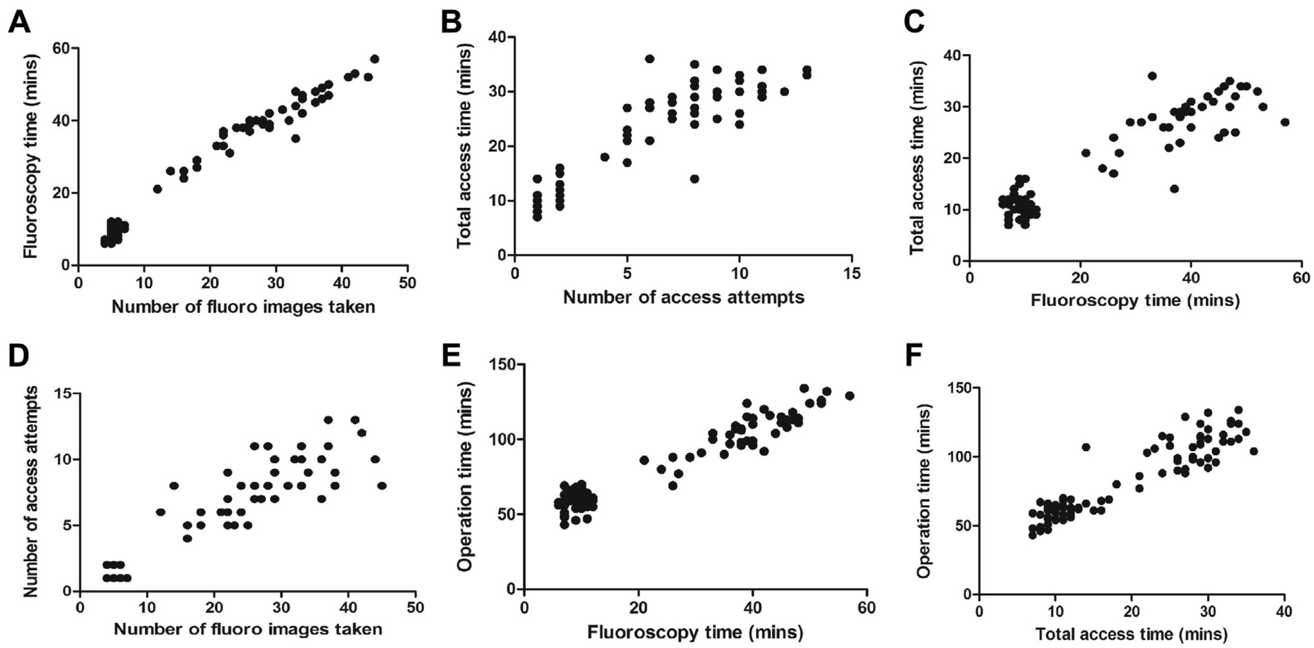

Figure 4. (**A**) Correlations between number of times fluoroscopy was used and total fluoroscopy time. (**B**) Correlations between number of times access attempts were made and access time. (**C**) Correlations between fluoroscopy time and access time. (**D**) Correlations between number of times that fluoroscopy was used and number of access/localization attempts. (**E**) Correlations between fluoroscopy time and operative time. (**F**) Correlations between access time and operative time.

localization was unwarrantable based on current evidence. Wei et al.[39] retrospectively reviewed 89 patients with LDH who underwent PELD using the O-arm, and the results of their study showed that O-arm could provide detailed multiplanar intraoperative imaging for PELD and enable the surgeon to ascertain the surgical anatomy, determine the optimal working trajectory, and improve the accuracy of surgery. Even so, there was no mention about operative time and radiation exposure in that study, and the major drawbacks of O-arm were radiation exposure and surgery cost. Chen et al.[40] and Hu et al.[41] used different preoperative planning software for access and location of PELD; both these showed that preoperative planning software could provide an ideal path for puncture in PELD; a significant reduction in channel establishment time, operative time, and

Table 3. Clinical Outcomes of Percutaneous Endoscopic Lumbar Discectomy Between Group A and Group B

Variables	Group A	Group B	*P* Value
Visual analog score (SD)			
Preoperative back	6.2 (1)	6.0 (1)	0.462
Postoperative back	1.5 (0.9)	1.7 (0.8)	0.205
Preoperative leg	5.9 (1.2)	5.6 (1.1)	0.204
Postoperative leg	1.6 (0.8)	1.6 (0.8)	0.782
Japanese Orthopaedic Association score (SD)			
Preoperative	17.5 (2.7)	17.8 (2.6)	0.599
Postoperative	24.1 (2.2)	23.4 (2.3)	0.118
Oswestry Disability Index (SD)			
Preoperative	40.5 (3.3)	40.6 (3.1)	0.973
Postoperative	17.1 (3.1)	18.3 (3.3)	0.097

SD, standard deviation.

Table 4. Magnetic Resonance Imaging Views of Lumbar and Complications Between Group A and Group B

Variables	Group A	Group B	*P* Value
Magnetic resonance imaging views			
Preoperative anteroposterior canal diameter (mm) (SD)	5.3 (0.8)	5.4 (0.8)	0.487
Postoperative anteroposterior canal diameter (mm) (SD)	8.3 (0.9)	8.2 (1.0)	0.495
Preoperative axial central canal area (mm^2) (SD)	147.0 (7.5)	150.0 (8.9)	0.096
Postoperative axial central canal area (mm^2) (SD)	159.7 (4.3)	161.4 (4.5)	0.079
Complications	7	8	0.776
Recurrence	3	2	1
Remnants	4	6	0.737

fluoroscopy times was achieved in Hu et al.'s study. Nevertheless, there is still no conclusive evidence to confirm the efficacy of this technique because of the low sample size of their studies and the accuracy of intraoperative location was susceptible to error. Zhao et al.[42] reviewed 6 patients who underwent PELD with the help of ultrasound volume navigation in 2017; the study showed that ultrasound volume navigation could decrease the puncture times, radiation exposure, and operation time in PELD. However, small sample size was one limitation in that study and longtime ultrasonography training for spine surgeons was necessary before engaging in PELD. Although improvements have been shown, the technical requirements of most new methods introduced were complex and difficult to popularize in clinical application.

In the past several years, computer-assisted navigation systems have been used for the placement of lumbar, thoracic, and cervical pedicle screws.[43-45] Multiple clinical studies have shown the accuracy of these navigation systems for screw placement as superior to conventional fluoroscopy methods.[45-47] Recently, 3D printing technology has developed rapidly in medicine, including medical products.[48-50] The main advantages of 3D printing are its flexibility, precision, and relative quickness in fabricating customized instrumental structures of almost any complex shape.[51,52] Considering the advantages of computer-assisted navigation systems and 3D printing technology, in this study, we designed a 3D-printed navigation cannula (with a small tip in the distal part used for facilitating a stab incision and a handle at the proximal end used for connecting the navigation receiver), which met our need and could be connected to fluoroscopy-based navigation systems. By using the navigation cannula and fluoroscopy-based navigation, surgeons can adjust the access angle and depth dynamically according to navigation feedback in real time until development of the working channel in a safe and accurate location. This technique could increase the likelihood of a single-attempt PELD approach to reach the target and significantly reduce the operative, fluoroscopy, access/localization times, and number of fluoroscopy and access/exposure attempts that are needed.

In our study, operative, fluoroscopy, and access/localization times were significantly lower using a fluoroscopy-based navigation technique for PELD compared with a conventional fluoroscopy-guided technique. These technical improvements also showed significant correlations between fluoroscopy and operative and access/localization time and operative time, signifying that reductions in operative steps through more efficient techniques decrease overall radiation exposure to the surgical team and patient and decrease operative time for the patient and staff. Thus, PELD using a fluoroscopy-based navigation system can minimize radiation exposure by reducing all major localization and access times and attempts. A more efficient overall procedure, shown by reductions in all primary end points, with similar radiographic and clinical outcomes, compared with conventional techniques, would likely decrease risks to patients and hospital staff and increase confidence of junior surgeons, hastening progress through the learning curve. In addition, the tools required for navigation are not foreign to surgeons and should not introduce significant variation in standard PELD techniques, outside access and localization.

When using fluoroscopy-based navigation for access and location, the following issues should be noted. 1) The surgeon must be familiar with the navigation system and make sure that the operation of each link is accurate. 2) The electro-optical camera of the navigation system should be placed at close range facing the navigation reference frame, and there should be no objects obstructing the electro-optical camera view and navigation reference frame to ensure the best receiving of infrared tracking information. 3) The navigation reference frame must be firmly fixed. If it is loose during the operation, access and localization may be poor because of reduction of the accuracy of the navigation system, which may increase the risk of dural sac and nerve root injury. 4) The X-ray tube of the C-arm should be vertical to the patient to obtain standard anteroposterior and lateral X-ray images. 5) Before intervertebral foraminoscopy, the guide wire and casing pipe should be confirmed by the anteroposterior and lateral position X-ray films. 6) Navigation accuracy can be referenced by bony anatomic landmark markings on the skin (e.g., spinous process and iliac crest). 7) The location of the working channel is a key, but only the first step in PELD; junior surgeons still need to accumulate their experience of pathologic exposure and the steps of endoscopic discectomy.

This study has several limitations. The retrospective design is a weakness, but bias was limited by the inclusion of all patients treated with PLED at the institution. Also, the use of fluoroscopy may not be an exact proxy for radiation emission, because dose per image was not controlled for or calculated. In addition, most patients had low BMI; more patients with high BMI should be considered because obesity is a risk factor for LDH that may increase the difficulty of surgery.

CONCLUSIONS

PELD, assisted with fluoroscopy-based navigation, can result in reduced operative, fluoroscopy (radiation), and access/localization time. Lower fluoroscopy (radiation) times and fluoroscopy (radiation) time was associated with lower access/localization times and operation time.

ACKNOWLEDGMENTS

The authors would like to thank Kyle Malone, M.S. and Chun-po Yen, M.D. for their editorial and statistical support of this manuscript.

REFERENCES

1. Aizawa T, Tanaka Y, Yokoyama T, et al. New diagnostic support tool for patients with leg symptoms caused by lumbar spinal stenosis and lumbar intervertebral disc herniation: a self-administered, self-reported history questionnaire. *J Orthop Sci*. 2016;21:579-585.
2. Hincapie CA, Tomlinson GA, Cote P, Rampersaud YR, Jadad AR, Cassidy JD. Chiropractic care and risk for acute lumbar disc herniation: a population-based self-controlled case series study. *Eur Spine J*. 2018;27:1526-1537.
3. Li H, Jiang C, Mu X, Lan W, Zhou Y, Li C. Comparison of MED and PELD in the treatment of adolescent lumbar disc herniation: a 5-year retrospective follow-up. *World Neurosurg*. 2018; 112:e255-e260.
4. Kim MH, Lee YJ, Shin JS, et al. The long-term course of outcomes for lumbar intervertebral disc herniation following integrated complementary and alternative medicine inpatient treatment: a prospective observational study. *Evid Based Complement Alternat Med*. 2017;2017:5239719.
5. Lurie JD, Henderson ER, McDonough CM, et al. Effect of expectations on treatment outcome for lumbar intervertebral disc herniation. *Spine (Phila Pa 1976)*. 2016;41:803-809.
6. Madhok R, Kanter AS. Extreme-lateral, minimally invasive, transpsoas approach for the treatment of far-lateral lumbar disc herniation. *J Neurosurg Spine*. 2010;12:347-350.
7. Peul WC, van den Hout WB, Brand R, Thomeer RT, Koes BW. Prolonged conservative care versus early surgery in patients with sciatica caused by lumbar disc herniation: two year results of a randomised controlled trial. *BMJ*. 2008;336: 1355-1358.
8. Veresciagina K, Spakauskas B, Ambrozaitis KV. Clinical outcomes of patients with lumbar disc herniation, selected for one-level open-discectomy and microdiscectomy. *Eur Spine J*. 2010; 19:1450-1458.
9. Liu X, Yuan S, Tian Y, et al. Comparison of percutaneous endoscopic transforaminal discectomy, microendoscopic discectomy, and microdiscectomy for symptomatic lumbar disc herniation: minimum 2-year follow-up results. *J Neurosurg Spine*. 2018;28:317-325.
10. Lee S, Kim SK, Lee SH, et al. Percutaneous endoscopic lumbar discectomy for migrated disc herniation: classification of disc migration and surgical approaches. *Eur Spine J*. 2007;16:431-437.
11. Liu C, Chu L, Yong HC, Chen L, Deng ZL. Percutaneous endoscopic lumbar discectomy for highly migrated lumbar disc herniation. *Pain Physician*. 2017;20:E75-E84.
12. Wu X, Fan G, Gu X, Guan X, He S. Surgical outcome of two-level transforaminal percutaneous endoscopic lumbar discectomy for far-migrated disc herniation. *Biomed Res Int*. 2016;2016, 4924013.
13. Passacantilli E, Lenzi J, Caporlingua F, et al. Full endoscopic transforaminal endoscopic approach for symptomatic lumbar disc herniation, our experience. *J Neurosurg Sci*. 2016;60:410-412.
14. Eun SS, Lee SH, Liu WC, Erken HY. A novel preoperative trajectory evaluation method for L5-S1 transforaminal percutaneous endoscopic lumbar discectomy. *Spine J*. 2018;18:1286-1291.
15. Nakamura JI, Yoshihara K. Initial clinical outcomes of percutaneous full-endoscopic lumbar discectomy using an interlaminar approach at the L4-L5. *Pain Physician*. 2017;20:E507-E512.
16. Yokosuka J, Oshima Y, Kaneko T, Takano Y, Inanami H, Koga H. Advantages and disadvantages of posterolateral approach for percutaneous endoscopic lumbar discectomy. *J Spine Surg*. 2016; 2:158-166.
17. Wood MJ, McMillen J. The surgical learning curve and accuracy of minimally invasive lumbar pedicle screw placement using CT based computer-assisted navigation plus continuous electromyography monitoring—a retrospective review of 627 screws in 150 patients. *Int J Spine Surg*. 2014;8.
18. Yang BP, Wahl MM, Idler CS. Percutaneous lumbar pedicle screw placement aided by computer-assisted fluoroscopy-based navigation: perioperative results of a prospective, comparative, multicenter study. *Spine (Phila Pa 1976)*. 2012;37: 2055-2060.
19. Wu H, Gao ZL, Wang JC, Li YP, Xia P, Jiang R. Pedicle screw placement in the thoracic spine: a randomized comparison study of computer-assisted navigation and conventional techniques. *Chin J Traumatol*. 2010;13:201-205.
20. Patton AG, Morris RP, Kuo YF, Lindsey RW. Accuracy of fluoroscopy versus computer-assisted navigation for the placement of anterior cervical pedicle screws. *Spine (Phila Pa 1976)*. 2015;40: E404-410.
21. Ohnsorge JA, Salem KH, Ladenburger A, Maus UM, Weisskopf M. Computer-assisted fluoroscopic navigation of percutaneous spinal interventions. *Eur Spine J*. 2013;22:642-647.
22. Han W, Gao ZL, Wang JC, et al. Pedicle screw placement in the thoracic spine: a comparison study of computer-assisted navigation and conventional techniques. *Orthopedics*. 2010;33.
23. Fan G, Gu X, Liu Y, et al. Lower learning difficulty and fluoroscopy reduction of transforaminal percutaneous endoscopic lumbar discectomy with an accurate preoperative location method. *Pain Physician*. 2016;19:E1123-E1134.
24. Guan X, Gu X, Zhang L, et al. Morphometric analysis of the working zone for posterolateral endoscopic lumbar discectomy based on magnetic resonance neurography. *J Spinal Disord Tech*. 2015; 28:E78-84.
25. Chen Z, Zhang L, Dong J, et al. Percutaneous transforaminal endoscopic discectomy compared with microendoscopic discectomy for lumbar disc herniation: 1-year results of an ongoing randomized controlled trial. *J Neurosurg Spine*. 2018;28: 300-310.
26. Peng CW, Yeo W, Tan SB. Percutaneous endoscopic lumbar discectomy: clinical and quality of life outcomes with a minimum 2 year follow-up. *J Orthop Surg Res*. 2009;4:20.
27. Yoon SM, Ahn SS, Kim KH, Kim YD, Cho JH, Kim DH. Comparative study of the outcomes of percutaneous endoscopic lumbar discectomy and microscopic lumbar discectomy using the tubular retractor system based on the VAS, ODI, and SF-36. *Korean J Spine*. 2012;9:215-222.
28. Choi KC, Kim JS, Park CK. Endoscopic lumbar discectomy as an alternative to open lumbar microdiscectomy for large lumbar disc herniation. *Pain Physician*. 2016;19:E291-E300.
29. Ahn Y, Kim CH, Lee JH, Lee SH, Kim JS. Radiation exposure to the surgeon during percutaneous endoscopic lumbar discectomy: a prospective study. *Spine (Phila Pa 1976)*. 2013;38:617-625.
30. Wu J, Zhang C, Zheng W, Hong CS, Li C, Zhou Y. Analysis of the characteristics and clinical outcomes of percutaneous endoscopic lumbar discectomy for upper lumbar disc herniation. *World Neurosurg*. 2016;92:142-147.
31. Ahn SS, Kim SH, Kim DW. Learning curve of percutaneous endoscopic lumbar discectomy based on the period (early vs. late) and technique (in-and-out vs. in-and-out-and-in): a retrospective comparative study. *J Korean Neurosurg Soc*. 2015;58: 539-546.

32. Kaminski L, Cordemans V, Cartiaux O, Van Cauter M. Radiation exposure to the patients in thoracic and lumbar spine fusion using a new intraoperative cone-beam computed tomography imaging technique: a preliminary study. *Eur Spine J*. 2017;26:2811-2817.

33. Prasarn ML, Coyne E, Schreck M, Rodgers JD, Rechtine GR. Comparison of image quality and radiation exposure from C-arm fluoroscopes when used for imaging the spine. *Spine (Phila Pa 1976)*. 2013;38:1401-1404.

34. Plastaras C, Appasamy M, Sayeed Y, et al. Fluoroscopy procedure and equipment changes to reduce staff radiation exposure in the interventional spine suite. *Pain Physician*. 2013;16:E731-738.

35. Zeng Y, Bao J, Su J, et al. Novel targeted puncture technique for percutaneous transforaminal endoscopic lumbar discectomy reduces X-ray exposure. *Exp Ther Med*. 2017;14:2960-2968.

36. Choi G, Modi HN, Prada N, et al. Clinical results of XMR-assisted percutaneous transforaminal endoscopic lumbar discectomy. *J Orthop Surg Res*. 2013;8:14.

37. Fan G, Han R, Gu X, et al. Navigation improves the learning curve of transforamimal percutaneous endoscopic lumbar discectomy. *Int Orthop*. 2017;41:323-332.

38. Fan G, Wang C, Gu X, Zhang H, He S. Trajectory planning and guided punctures with isocentric navigation in posterolateral endoscopic lumbar discectomy. *World Neurosurg*. 2017;103:899-905.e4.

39. Wei S, Tao W, Zhu H, Li Y. Three-dimensional intraoperative imaging with O-arm to establish a working trajectory in percutaneous endoscopic lumbar discectomy. *Wideochir Inne Tech Maloinwazyjne*. 2016;10:555-560.

40. Chen X, Cheng J, Gu X, Sun Y, Politis C. Development of preoperative planning software for transforaminal endoscopic surgery and the guidance for clinical applications. *Int J Comput Assist Radiol Surg*. 2016;11:613-620.

41. Hu Z, Li X, Cui J, et al. Significance of preoperative planning software for puncture and channel establishment in percutaneous endoscopic lumbar DISCECTOMY: a study of 40 cases. *Int J Surg*. 2017;41:97-103.

42. Zhao Y, Bo X, Wang C, et al. Guided punctures with ultrasound volume navigation in percutaneous transforaminal endoscopic discectomy: a technical note. *World Neurosurg*. 2018;119:77-84.

43. Quinones-Hinojosa A, Robert Kolen E, Jun P, Rosenberg WS, Weinstein PR. Accuracy over space and time of computer-assisted fluoroscopic navigation in the lumbar spine in vivo. *J Spinal Disord Tech*. 2006;19:109-113.

44. Zhang HL, Zhou DS, Jiang ZS. Analysis of accuracy of computer-assisted navigation in cervical pedicle screw installation. *Orthop Surg*. 2011;3:52-56.

45. Siasios ID, Pollina J, Khan A, Dimopoulos VG. Percutaneous screw placement in the lumbar spine with a modified guidance technique based on 3D CT navigation system. *J Spine Surg*. 2017;3:657-665.

46. Ling JM, Dinesh SK, Pang BC, et al. Routine spinal navigation for thoraco-lumbar pedicle screw insertion using the O-arm three-dimensional imaging system improves placement accuracy. *J Clin Neurosci*. 2014;21:493-498.

47. Allam Y, Silbermann J, Riese F, Greiner-Perth R. Computer tomography assessment of pedicle screw placement in thoracic spine: comparison between free hand and a generic 3D-based navigation techniques. *Eur Spine J*. 2013;22:648-653.

48. Wang L, Ye X, Hao Q, et al. Comparison of two three-dimensional printed models of complex intracranial aneurysms for surgical simulation. *World Neurosurg*. 2017;103:671-679.

49. Park SH, Choi YJ, Moon SW, et al. Three-dimensional bio-printed scaffold sleeves with mesenchymal stem cells for enhancement of tendon-to-bone healing in anterior cruciate ligament reconstruction using soft-tissue tendon graft. *Arthroscopy*. 2018;34:166-179.

50. Amelot A, Colman M, Loret JE. Vertebral body replacement using patient-specific three-dimensional-printed polymer implants in cervical spondylotic myelopathy: an encouraging preliminary report. *Spine J*. 2018;18:892-899.

51. Maroulakos M, Kamperos G, Tayebi L, Halazonetis D, Ren Y. Applications of 3D printing on craniofacial bone repair: a systematic review. *J Dent*. 2019;80:1-14.

52. Ricles LM, Coburn JC, Di Prima M, Oh SS. Regulating 3D-printed medical products. *Sci Transl Med*. 2018;10.

Conflict of interest statement: This work is supported by the National Natural Science Foundation Project of China (81760401), National Key R&D Program of China (2017YFC1103403), South Wisdom Valley Innovative Research Team Program (2015CXTD05), the Science and Technology Project of Guangdong Province (2015B010125005, 2016B090917001, 2016B090913004, 2017B090912006), Guangxi Science and Technology Base and Talent Specialization (AD17129017, AD17195042), and the Science and Technology Project of Guigang City (1803002).

Received 9 July 2018; accepted 31 January 2019

Citation: World Neurosurg. (2019) 127:e39-e48. https://doi.org/10.1016/j.wneu.2019.01.289

Journal homepage: ***www.journals.elsevier.com/world-neurosurgery***

Available online: ***www.sciencedirect.com***