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Development of a Virtual Reality Preoperative Planning System for Postlateral Endoscopic Lumbar Discectomy Surgery and Its Clinical Application

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OBJECTIVE: **Percutaneous endoscopic lumbar discectomy is an effective way to treat lumbar disc herniation. Traditional preoperative planning based on a 2-dimensional method by magnetic resonance/computed tomography may cause inaccuracy of puncture during surgery. We used virtual reality to stimulate a surgery environment and measured relevant 3-dimensional data. We then explored its applicability for increasing puncture accuracy during actual surgeries.**

METHODS: **A prospective randomized trial of lumbar disc herniation was conducted. Both conventional and virtual reality methods were used for preoperative planning and relevant data (planned puncture point and entry angle) were measured. Data were used during surgery and adjusted to complete the operation. The final entry point and entry angle were recorded and compared with relevant planned data statistically. Fluoroscopic times and location time also were included to access the puncture accuracy during surgery.**

RESULTS: **Thirty cases were included in our study. Both groups achieved good results after surgery, except for 1 case of postoperative dysesthesia in the traditional planning group and 1 case of residual disc in the virtual reality group. The use of virtual reality can predict a surgery-related angle and distance accurately except for depth. Compared with the traditional planning group, the fluoroscopic time (13.18 $\pm$ 4.191 vs. 32.00 $\pm$ 4.52) and location time (17.91 $\pm$ 4.74 vs. 33.22 $\pm$ 3.90) were statistically different, which indicates that this method can increase puncture accuracy.**

CONCLUSIONS: **A virtual reality planning system is an accurate preoperative planning method that can significantly improve the puncture accuracy of percutaneous endoscopic lumbar discectomy and reduce fluoroscopic and location times.**

INTRODUCTION

Taking into consideration the increasing proportion of elderly people, a greater prevalence of lumbar disc herniation is unavoidable. For elderly patients, recovery after lumbar spine open surgery[1] is slower and those with comorbidities have greater risks during the perioperative period.[2] Percutaneous endoscopic lumbar discectomy (PELD) can reduce unnecessary damage to the normal stabilized spine structure and has been proven to be a safe and effective method.[3]

However, the lack of an anatomy landmarks, steep learning curve, and radiation exposure are main concerns and at times are the cause of iatrogenic injury. Compared with open surgery, PELD has a much smaller operating field and thus depends on the accuracy of working tube insertion. An inappropriate working channel location causes up to one-third of incomplete disc removal and can cause severe complications such as injury of nerve and vessels.[4]

Key words
- Computed tomography
- Disc herniation
- Percutaneous endoscopic lumbar discectomy
- Preoperative planning
- Puncture accuracy
- Virtual reality

Abbreviations and Acronyms
2D: Two-dimensional
3D: Three-dimensional
CT: Computed tomography
MR: Magnetic resonance
PELD: Percutaneous endoscopic lumbar discectomy
VR: Virtual reality

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PELD surgery uses fluoroscopy to guide the insertion of equipment. Using a two-dimensional method (2D) in a three-dimensional (3D) surgery field can mislead the surgeon; also, it takes a long time to acquire the ability of understanding the location of the equipment, with the surgeon relying on his/her imagination and space capacity.[5] Preoperative planning is mostly based on the measurement of transverse plane of magnetic resonance (MR)/computed tomography (CT). Some surgeons use a fixed distance to determine the entry point based on their experience. For example, surgeons may apply 10 cm as a midline distance for L4–L5 disc herniation. For L5–S1, however, it is more difficult because of the high iliac crest, hypertrophy of transverse process, and small size of the foramina zone.[6] Finding an efficient 3D method that can precisely measure necessary data, to ensure the accuracy of insertion and avoid iatrogenic injuries, is urgent.

There are several ways of simulating surgery and preoperative planning, such as 3D printing,[7] finite element simulations,[8] and virtual reality (VR), which is a technique that can simulate an environment from many aspects and make subjects believe that they are actually in the environment. VR has been applied in many fields, such as games, the military, and aviation. As it can simulate the real world, it has been widely used for pilot training and attains a transfer rate of 50%. That is to say, training 2 hours in the simulator equals 1 hour in the real world.[9]

VR also has been used in research and can improve the accuracy of surgery manipulation. Färber et al.[10] developed a training VR system for epidural needle insertion that was proven effective in training medical students. Other VR-based systems also proved useful in training residents.[11] Abe et al.[12] even used VR to navigate needle insertion during percutaneous vertebroplasty surgery and improved puncture accuracy. As far as we know, however, no application of VR has been reported in PELD in a search of the literature.

In turn, we developed a preoperative VR system and verified its efficacy via its clinical application. In improving the accuracy of inserting through measuring the ideal entry point and direction preoperatively, we hope to reduce radiation exposure, operation time, and learning curve.

MATERIALS AND METHODS

General Information

This prospective randomized trial was approved by the institutional review board of Sun Yat-sen Memorial Hospital. Consent forms were obtained from all included patients before surgery. From December 1, 2016, patients undergoing PELD in the Orthopedic department of Sun Yat-sen Memorial Hospital were enrolled in this study. Inclusion criteria were 1) soft disc herniation producing radiating pain without foraminal stenosis, lateral recess stenosis, or any posterior pathology; 2) age >18 years old; 3) no severe mental illness or severe obesity; and 4) no response to conservative treatment for more than 6 weeks. The exclusion criteria were 1) multilevel lumbar intervertebral disc herniation, 2) highly migrated disc herniation, 3) combined with lumbar spondylolisthesis, instability, lumbar malformation, vertebral fractures, active infection, or other severe spinal diseases.

The patients were assigned a random number from 1 to 30 based on a random number table. Those with a number greater than 15 were distributed to the experimental group (group A) and the others were assigned as the control group (group B). The experimental group was exposed to the VR planning system, whereas the control group was exposed to the traditional 2-dimensional planning. The study primary endpoint was puncture-related data. The secondary endpoint was fluoroscopy times and location time (from the beginning of the first fluoroscopy to the end of the insertion). Basic information, including age, sex, surgical segment, and conservative treatment duration, was recorded.

VR Planning System

Images of lumbar (slice thickness was 1 mm, supine position) were acquired using spiral CT (Somatom Sensation 64; Siemens, Munich, Germany) and stored in the form of DICOM 3.0. Then, the image-processing software M-Visioneer was used to form a VR lumbar model (Figure 1). The MVisioneer (MVisioner limited, Shenzhen, China) processing software was developed by a Chinese company to process data collected from MR/CT and create a VR model that can be exhibited outside the screen. When the subject wears a pair of special glasses, the model seems to be a real object in the real world (Figure 1).

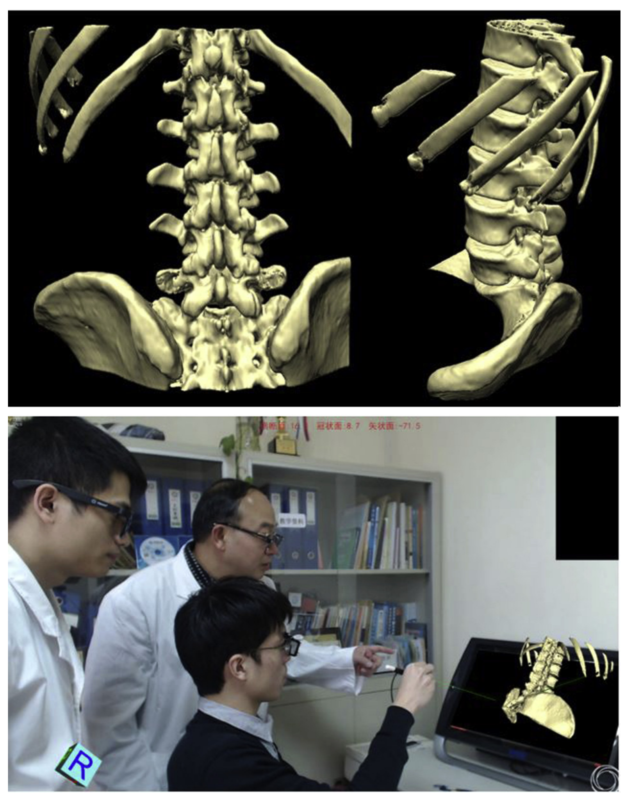

Figure 1. A virtual reality (VR) lumbar model created by VR-based software M-Visioneer; it can deceive the operator that it interfaces with the real world.

First, we used a VR-planning system to locate the targeted point in the virtual environment. We used the MR of patients to decide the target point of insertion and mark it on the 2D CT interface. Then, the software would create a working tube on the VR interface based on the marked point (Figure 2). The geographic position of the tip of the working tube and the marked point on the 2D interface was identical. Meanwhile, the system can reflect the space relationship between the virtual working tube and its surrounding structure accurately.

Second, we used a stylus pen to redirect the direction of the "virtual" working tube. The stylus pen uses infrared detectors to interact with the virtual world, and once it touches the end of the working tube, it can change the direction of it while not altering the position of its tip. In this manner, we can redirect the working tube to avoid colliding with superior articular processes and the iliac crest. At the bottom of the screen, the angle between the working tube and sagittal, coronal, and transverse planes were shown to synchronize with the alternation of the working tube. Then, a virtual radiograph can be created using our system (Figure 2).

Third, we recreated the skin on the VR lumbar model and found the intersection point between the working tube and skin. Then, we measured the distance between the intersection point and midline and defined it as the "midline distance." Next, we measured the distance on the model's skin between the intersection point and upper surface of the lower vertebral body and defined it as "vertical distance." The depth of the working tube also was calculated (Figure 3). The procession mentioned here was conducted by our software. The operator only needs to define midline and the upper surface, reducing the operation time.

Conventional Planning System

For patients in the control group, we arranged radiography/CT/MR and used the data to predict the entry point and entering direction (Figure 4). First, we marked a line through the upper one-third of the superior articular process and disc herniation part on the anteroposterior view (line A) and measured its angle with the horizontal line (angle A, standing for angle between working tube and transverse plane). Then, we marked a line going through the upper one-third of the superior articular process and posterior line of the vertebral body on the lateral view (line B). We defined the intersection point between line B and the skin as point A. Next, we marked a line going through the upper border of the lower vertebral body, defining its intersection point with skin as point B. We recorded the distance between point A and B and defined it as the "vertical distance."

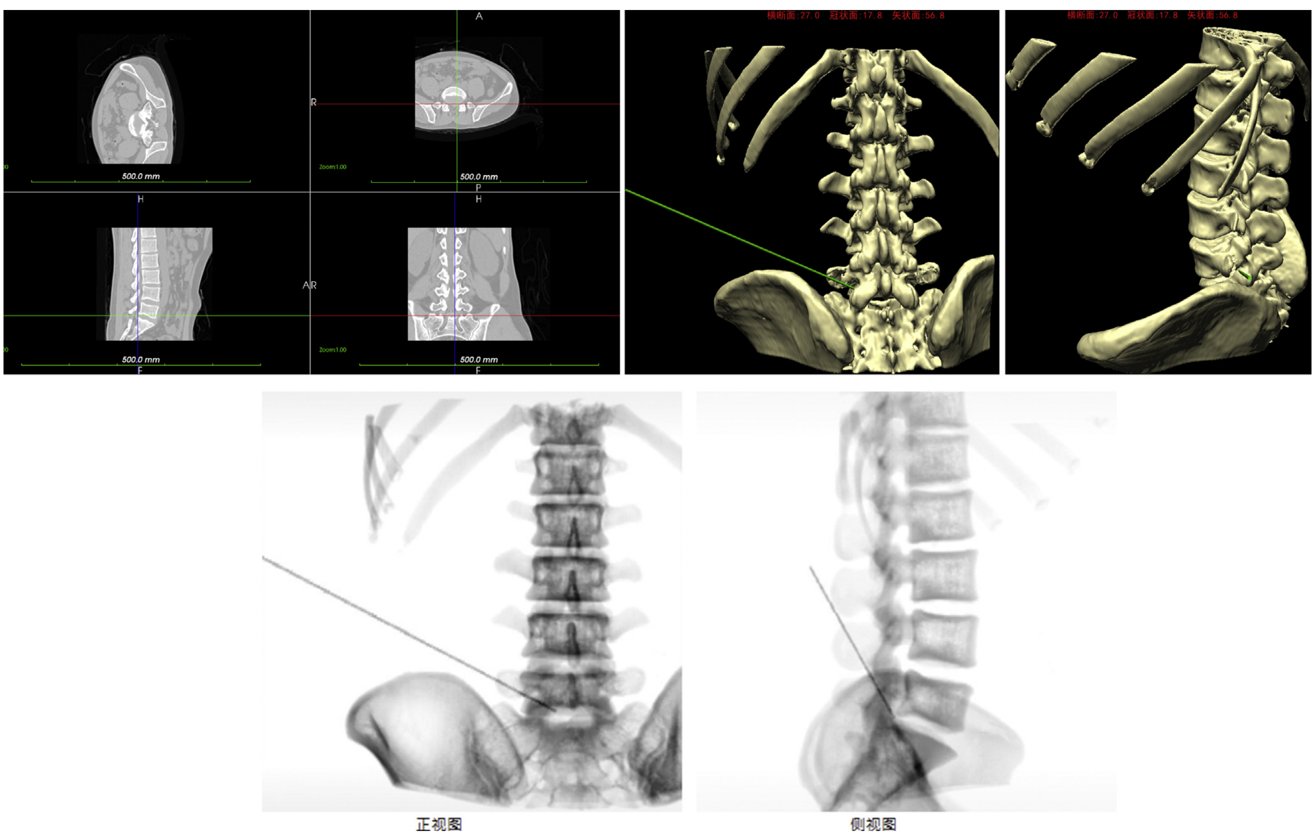

Figure 2. Choosing a target point on computed tomography and automating create the puncture needle on the model; then, a virtual radiograph is simulated and a virtual X-ray was simulated accordingly.

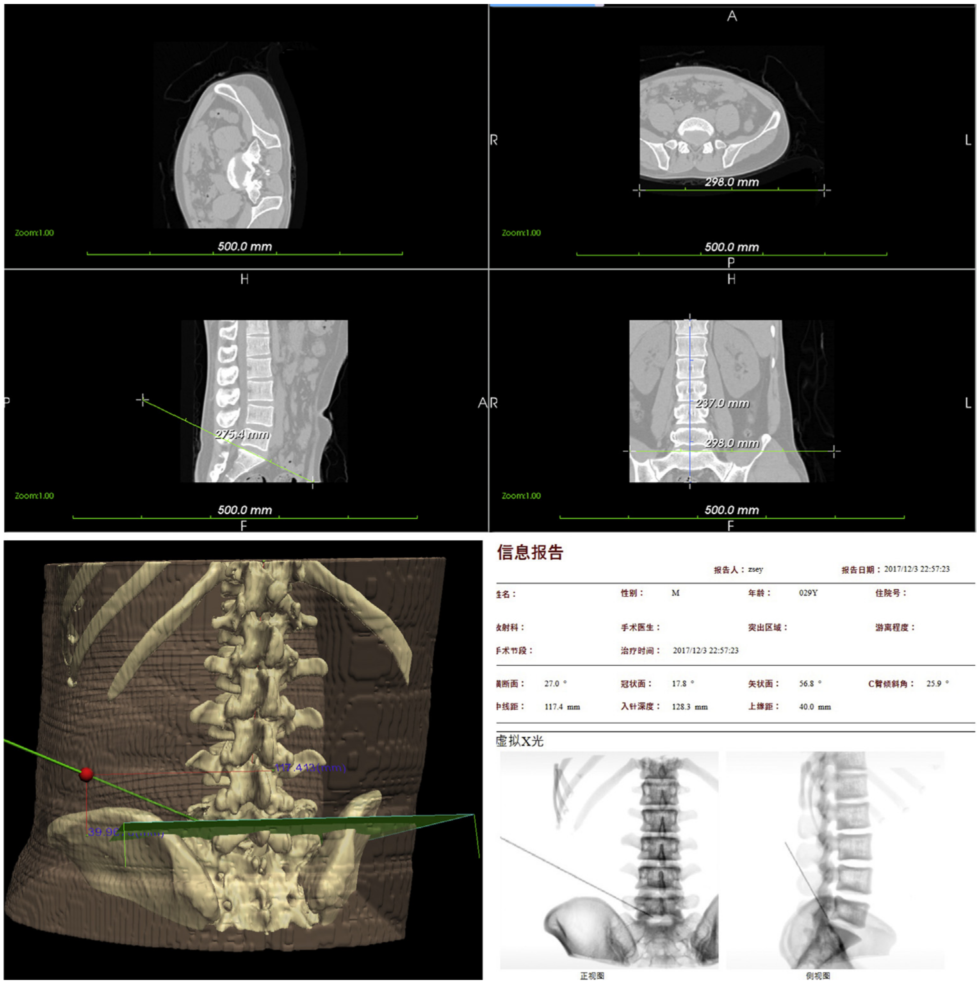

Figure 3. Defination of midline and upper surface of the lower vertebral body on a 2-dimensional interface; relevant data were calculated automatically.

We used the transverse plane of MR and marked a line going through the superior articular process and the disc herniation part (line C). Its intersection point with skin is point C. The angle between line C and horizonal line was recorded as angle B, which stands for the angle between working tube and the coronal plane. The distance between point C and the target point was defined as the depth. Then we measured the distance between point C and the midline of the patient's body and defined it as the "midline distance."

Surgical Procedure

For patients in both groups, they were placed in a prone position on a radiolucent operating table in a conscious state under local anesthesia. Then, a gradienter was introduced to make sure the patient's back was level and simulating the status while taking the CT (Figure 5). Next, we obtained standard anteroposterior and lateral fluoroscopy by C-arm. The patients were told to stay still during the insertion and report radiation pain to the surgeon to avoid injuring the nerves. Then, we used marker pens to mark the midline and a line parallel to the upper border of the lower vertebral body according to the Ferguson view.

In both groups, we used the "vertical distance" and "midline distance" to locate the entry point. Then, we used a protractor to guide the entering direction based on our calculated data. After disinfection, we entered an 18-G puncture needle to the exact puncture target and replaced the equipment with the same entering length till insertion of the working tube. Then the angle, distance, and depth mentioned previously were calculated as realist data. The following procedures were the same as was done in conventional processes.

Statistical Analysis

SPSS 18.0 (SPSS Corp., Chicago, Illinois, USA) was adopted to conduct the statistical analysis. Enumeration data are demonstrated as mean ± SD or median, quartiles. The independent

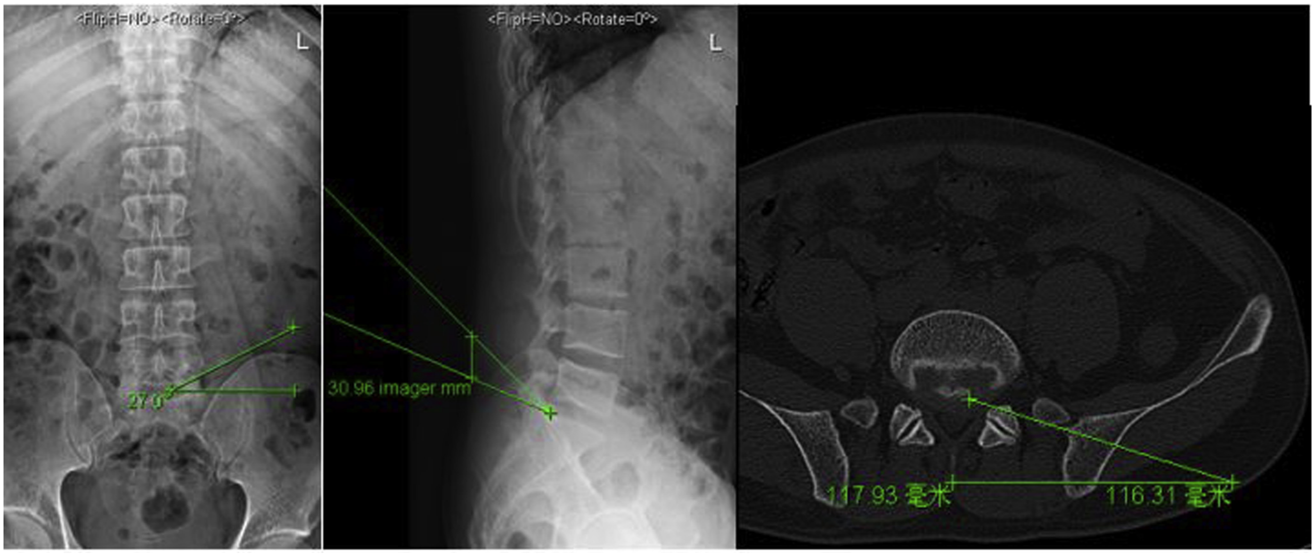

Figure 4. Use of radiography/computed tomography/magnetic resonance imaging to calculate the related distance and angle.

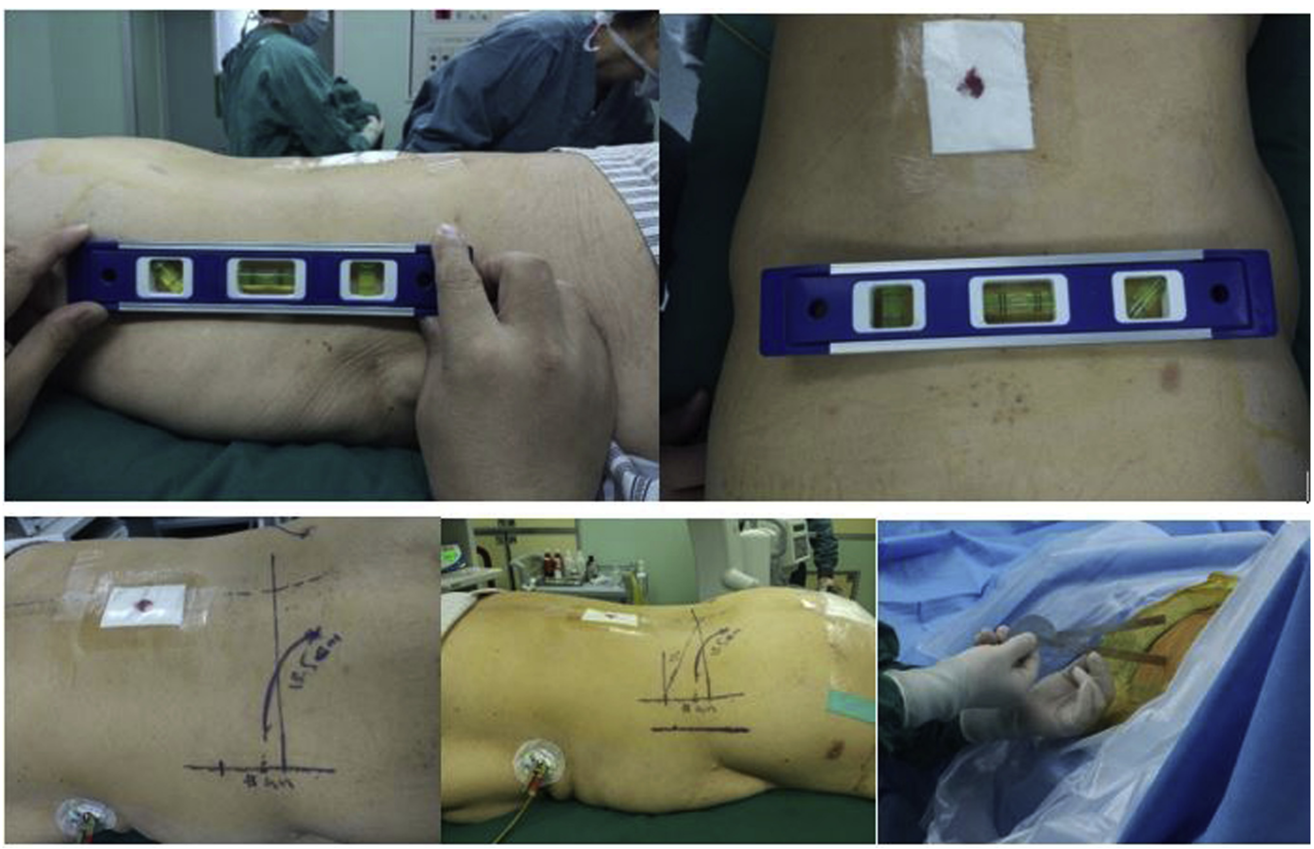

Figure 5. A gradienter was introduced to make sure the back is level. A C-arm was introduced to find the upper surface line on the skin; then, the calculated data were applied.

Table 1. Sociodemographic and Clinical Characteristics of the Patients

	VR Group	Conventional Group
No. patients	15	15
Average age, years	49.8 ± 14.83	55.9 ± 13.27
Conservative time, months	36 (12, 36)	24 (3.5, 66)
No. for each segment		
L4—L5	11	9
L5—L1	2	6
L3—L4	2	0
Preoperative ODI, %	56.67 ± 7.35	65.67 ± 9.15
Postoperative ODI, %	9.20 ± 3.76*	10 (8, 16)*
Preoperative leg pain VAS score	6.8 ± 1.32	7 (6, 8)
Postoperative leg pain VAS score	1 (1, 2)*	2 (2, 3)*

Data are demonstrated as mean ± SD or median, quartiles.
VR, virtual reality; ODI, Oswestry Disability Index; VAS, visual analogue scale.
*For ODI and VAS, scores after surgery are statistically less than before and there are no differences between the 2 groups. There are no statistically difference between the 2 groups regarding other sociodemographic and clinical characteristics.

Student t test was used to compare the difference of continuous variables between the 2 groups when data were normally distributed. The Mann−Whitney U test was used to compare the difference of continuous variables between the 2 groups, whereas data were non-normally distributed. $P < 0.05$ was considered as statistically significant.

RESULTS

By December 31, 2017, a total of 30 patients who received PELD were included in this study with 15 cases in either group (Figure 5). All 30 included patients who completed the PELD surgery, and intraoperative blood loss was negligible without blood transfusion. There were 9 men and 6 women in group A and there were 7 men and 8 women in group B ($P = 0.157$). The average age was 49.8 ± 14.83 years in group A and 55.9 ± 13.27 years in group B ($P = 0.243$). The conservative time was 36 (12, 36) months in group A and 24 (3.5, 66) months in group B ($P = 0.397$). For the Oswestry Disability Index and visual analogue scale, scores after surgery are statistically less than before and there are no differences between the 2 groups. There are 11 L4—L5, 2 L5—S1, and 2 L3—L4 in group A and 9 L4—L5 and 6 L5—S1 in group B ($P = 0.223$) (Table 1).

For puncture-related data, we used L4—L5 only to reduce bias and compare planned data with realist data. Group A had no statistic difference between planned data and realist data except the depth. Group B had a statistical difference between angle and distance but no difference between depths. The fluoroscopy times were 13.18 ± 4.191 in group A and 32.00 ± 4.52 in group B ($P < 0.001$). The location time was 17.91 ± 4.74 in group A and 33.22 ± 3.90 in group B ($P < 0.001$). There was 1 case of postoperative dysesthesia in group B and 1 case of residual disc in group B (Tables 2 and 3).

DISCUSSION

In our study, we developed a preoperative VR system for the precise measurement of puncture-related clinical data and applied it during surgery. The statistics show that it can predict the entry point and direction before surgery, except depth. In contrast, a traditional planning approach cannot predict precisely and needs more adjustments than the former. We assume that indicates an advantage in the use of 3D methods over 2D methods. Moreover, we can observe more anatomical detail with a VR effect.

To reduce influence of patient's posture on lumbar lordosis and ensure the accuracy of planning system, we measure the "vertical distance" from the upper surface of lower lumbar vertebral body rather than from a fixed structure like the iliac crest because the distance is short and can ensure its accuracy because the upper surface change with posture and adjunct to our target. Also, we measure the angle between surface and horizontal line on CT and make sure it's applied during surgery. Third, we use a gradienter to make sure the back is flat just like when patient were undergoing CT. Finally, our data show that our method is reliable.

Table 2. Puncture-Related Data of the Patients

		Midline Distance		Vertical Distance		Coronal Angle		Transverse Angle		Depth	
Group	No.	Planned	Actual	Planned	Actual	Planned	Actual	Planned	Actual	Planned	Actual
VR	11	115.69 ± 16.72	114.27 ± 14.19	36.06 ± 12.27	35.93 ± 12.68	23.18 ± 7.51	23.08 ± 7.15	19.77 ± 2.39	20.55 ± 2.544	127.9 ± 19.08*	122.55 ± 14.73
Conventional	9	106.67 ± 16.82*	113.33 ± 8.57	34.86± 8.00*	30 (25, 33.5)	28.09 ± 8.08*	21.44 ± 3.84	26.09 ± 5.17*	20.78 ± 2.635	118.22 ± 11.53	119.00 ± 8.28

Data are demonstrated as mean ± SD or median, quartiles.
VR, virtual reality.
*For puncture-related data, we compared planned date and realistic data. Results show that there is no difference between them except the depth in VR group, whereas in the conventional group, there is a statistical difference between the data except the depth.

Table 3. Radiology-Related Data of the Patients

Group	Location Time	Fluoroscopy Time
VR	17.91 ± 4.74*	13.18 ± 4.191*
Conventional	33.22 ± 3.90*	32.00 ± 4.52*

Data are demonstrated as mean ± SD.
VR, virtual reality.
*The location time and fluoroscopy time in VR group are statistically less than the conventional group.

Accuracy of the working tube insertion is the base of PELD and the main obstacle in learning the technique. A wrong or inaccurate insertion can cause many problems, such as iatrogenic injury, longer operation time, remnant of disc herniation, and transfer to open surgery. Approximately 65% of unsuccessful PELDs were caused by incomplete removal of disc herniation; inappropriate working tube location was the main cause of incomplete removal.[4]

Our results show that VR preoperative planning can reduce fluoroscopy and location times. However, there were no clinical differences between the 2 groups. We consider the causation is that our surgery was conducted by a senior spine surgeon who has operated more than 500 minimally spine surgeries. When the working tube insertion is inaccurate, our surgeon can adjust its location and thus have a good clinical result. Nonetheless, the procedure is time-consuming without VR planning and increases the possibility of nerve surgery. For a less-experienced doctor, such a condition can even cause remnant of disc herniation and other complications mentioned above. In turn, we deduce that our VR planning system can increase the success time of the procedure among less experienced doctors.

Accuracy of working tube insertion is important. There are several ways of resolving this problem, such as foraminoplasty,[13] a trans-iliac approach,[14,15] or interlaminar approach.[16] However, the methods mentioned previously focus on the completion of operation but not the accuracy of insertion and also can cause problems such as instability, blood loss, and injury of paraspinal muscles.

Radiation exposure is another key concern in PELD surgery, for it can cause stochastic and deterministic adverse events.[17] At L5—S1, the average exposure doses are about 1.5 times compared with segments above it. And, for the novice, the fluoroscopy time was 3.5 times the average time of a senior surgeons.[5] The VR planning system in our study reduced the exposure by a minimum of fluoroscopy times. With the help of preoperative planning, we only needed fine adjustment to reach the targeted point and avoid repeated adjustments.

The greatest advantage of a VR planning system is that it can introduce a working tube into a VR model and simulate the actual insertion process. By adjusting the targeted point, entry direction, and skin entry point, we can observe the relationship between the working tube and iliac crest, transverse process, and superior articular process synchronously. Furthermore, we can estimate whether to perform foraminoplasty before surgery. For patients unsuitable for PELD, we can transfer to open surgery before operation and avoid unnecessary iatrogenic injury.

Compared with traditional 3D reformats on a computer workstation, our planning system provides added value. First, there is no other workstation specially designed for PELD surgery. Our system can plan the procedure step by step and only takes about 5 minutes for each person without any difficulty in computer operation. The procedure is semiautomatic. Second, our system can represent realistic anatomic detail and improve depth visualization. It can provide a dynamic image that can be rotated according to the operator's visual angle. Third, traditional working stations fundamentally are screenshots of a 3D model, but VR can represent a virtual 3D model. Fourth, our system provides virtual radiographic results, which can be used for preoperative practice and intraoperative appliance.

As mentioned previously, VR can provide a virtual 3D object rather than screenshots. Thus, when planning trajectories, the operator only needs to adjust his or her visual angle just like in the real world, rather than use a mouse to click, which is convenient and time-saving. Our system includes a 2D interface and virtual 3D interface, which can be shown synchronously. We can define midline and upper surface on the 2D interface and the system can construct the related structure on a 3D interface and calculate data automatically. As far as we know, there is no system that can identify incision location, whereas our system can identify it automatically.

Presently, innovations in medical imaging show shifts from 2D to 3D methods, with 3D printing and O-arm navigation showing effectiveness as methods in improving the accuracy of pedicle screws and other equipment.[18,19] 3D printing can print patient-specific models and is mainly used in preoperative surgery in open surgery. At the same time, however, 3D printing is material-consuming and is unable to calculate the distance and angle accurately. While O-arm navigation can improve the learning curve of PELD and accuracy of working tube insertion, it is not widely adopted because of its expensive cost, especially in developing countries. A VR planning system, which can measure the exact distance and angle in a 3D environment, is cheap and can be used for navigation. For example, a novel 3D guidance system used for percutaneous vertebroplasty only requires a web camera and head mount display, at a cost of about $1000.[12]

Both the potential and some limitations of a VR planning system should be further noted. Unlike open surgery, minimally invasive spine surgery has a steep learning curve, preventing many novices from mastering it. The effectiveness of a VR planning system on the learning curve is under research. A VR planning system also can be used to train residents, which is also a further part of our study. In our study, we demonstrated the relationship between using a preoperative planning system and fluoroscopy times and location times. However, we did not demonstrate the influence of a VR planning system on patients' clinical outcome, due to time limitations. We will collect data from our patients later on. Also, unlike in many other studies, because of limitations in our equipment, we did not demonstrate the radiation dosage of the surgeons.[20,21] We will demonstrate the effect of radiation reduction in further studies.

CONCLUSIONS

VR planning system is an accurate preoperative planning method, significantly improving the puncture accuracy of PELD and reducing fluoroscopic and location times. This study indicates the significant benefit of a VR planning system in minimizing puncture injury and radiation exposure of PELD, which may have considerable potential application in clinical practice. Further research studying the relationship of a VR planning system and the learning curve and clinical outcome are also under investigation.

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REFERENCES

1. Gautschi OP, Smoll NR, Joswig H, Corniola MV, Schaller K, Hildebrandt G, et al. Influence of age on pain intensity, functional impairment and health-related quality of life before and after surgery for lumbar degenerative disc disease. *Clin Neurol Neurosurg*. 2016;150:33-39.

2. Koerner JD, Glaser J, Radcliff K. Which variables are associated with patient-reported outcomes after discectomy? Review of SPORT disc herniation studies. *Clin Orthop Relat Res*. 2015;473:2000-2006.

3. Sheng-Hua HE, Peng JY. Percutaneous endoscopic lumbar discectomy for the treatment of lumbar disc herniation. *China J Orthop Traumatol*. 2011;24:72-74.

4. Choi KC, Lee JH, Kim JS, Sabal LA, Lee S, Kim H, et al. Unsuccessful percutaneous endoscopic lumbar discectomy: a single-center experience of 10,228 cases. *Neurosurgery*. 2015;76:372-380.

5. Iprenburg M, Wagner R, Godschalx A, Telfeian AE. Patient radiation exposure during transforaminal lumbar endoscopic spine surgery: a prospective study. *Neurosurg Focus*. 2016;40:E7.

6. Hurday Y, Xu B, Guo L, Cao Y, Wan Y, Jiang H, et al. Radiographic measurement for transforaminal percutaneous endoscopic approach (PELD). *Eur Spine J*. 2017;26:635-645.

7. Chen H, Wu D, Yang H, Guo K. Clinical use of 3D printing guide plate in posterior lumbar pedicle screw fixation. *Med Sci Monit*. 2015;21:3948-3954.

8. Pfeiffer FM. The use of finite element analysis to enhance research and clinical practice in orthopedics. *J Knee Surg*. 2016;29:149-258.

9. Satava RM, Jones SB. Current and future applications of virtual reality for medicine. *Proc IEEE*. 1998;86:484-489.

10. Färber M, Hummel F, Gerloff C, Handels H. Virtual reality simulator for the training of lumbar punctures. *Method Inform Med*. 2009;48:493.

11. Alaraj A, Charbel FT, Birk D, Tobin M, Luciano C, Banerjee PP, et al. Role of cranial and spinal virtual and augmented reality simulation using immersive touch modules in neurosurgical training. *Neurosurgery*. 2013;72(suppl 1):115-123.

12. Abe Y, Sato S, Kato K, Hyakumachi T, Yanagibashi Y, Ito M, et al. A novel 3D guidance system using augmented reality for percutaneous vertebroplasty: technical note. *J Neurosurg Spine*. 2013;19:492-501.

13. Choi KC, Park CK. Percutaneous endoscopic lumbar discectomy for l5-s1 disc herniation: consideration of the relation between the iliac crest and L5-S1 disc. *Pain Physician*. 2016;19:E301-E308.

14. Gun C, Jin-Sung K, Pramod L, Sang-Ho L. Percutaneous endoscopic lumbar discectomy by transiliac approach: a case report. *Spine (Phila Pa 1976)*. 2009;34:443-446.

15. Osman SG, Sherlekar S, Malik A, Winters C, Grewal PK, Narayanan M, et al. Endoscopic transiliac approach to L5-S1 disc and foramen—a report on clinical experience. *Int J Spine Surg*. 2014;8:1-12.

16. Choi G, Prada N, Modi HN, Vasavada NB, Kim JS, Lee SH. Percutaneous endoscopic lumbar herniectomy for high-grade down-migrated L4-L5 disc through an L5-S1 interlaminar approach: a technical note. *Minim Invasive Neurosurg*. 2010;53:147-152.

17. Brenner DJ, Doll R, Goodhead DT, Hall EJ, Land CE, Little JB, et al. Cancer risks attributable to low doses of ionizing radiation: assessing what we really know. *Proc Natl Acad Sci U S A*. 2003;100:13761-13766.

18. Provaggi E, Leong JJ, Kalaskar DM. Applications of 3D printing in the management of severe spinal conditions. *Proc Inst Mech Eng H*. 2017;231:471-486.

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

20. Mroz TE, Yamashita T, Davros WJ, Lieberman IH. Radiation exposure to the surgeon and the patient during kyphoplasty. *J Spinal Disord Tech*. 2008;21:96-100.

21. Mroz TE, Abdullah KG, Steinmetz MP, Klineberg EO, Lieberman IH. Radiation exposure to the surgeon during percutaneous pedicle screw placement. *J Spinal Disord Tech*. 2011;24:264-267.

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