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Original Article

Centrifuge trephine-guided foraminoplasty in endoscopic lumbar discectomy: a laboratory and clinical evaluation

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Abstract: Objectives: Accurate placement of the working cannula during foraminoplasty remains a technical challenge in percutaneous transforaminal endoscopic lumbar discectomy (TELD). To address this, we developed a novel centrifuge trephine system designed to improve placement accuracy and provide a self-correcting trajectory. This study aimed to compare its performance with that of conventional trephine systems. Methods: This investigation comprised a laboratory simulation and a retrospective clinical study. In the laboratory, life-size 3D-printed lumbar models were used to compare operative time, fluoroscopic exposure, and cannula-to-herniation distance between the modified and conventional systems. Clinically, 101 patients with at least one year of follow-up were analyzed. Outcome measures included operative time, fluoroscopy times, cannula-herniation distance, postoperative dysesthesia, visual analog scale (VAS) scores for leg and back pain, Oswestry Disability Index (ODI), re-herniation, and reoperation rates. Statistical analyses were performed using the Mann-Whitney U test for continuous variables and the χ^2 test for categorical variables. Results: The modified system significantly reduced operative time and fluoroscopy exposure in both laboratory and clinical settings ($P < 0.001$). Clinically, it also resulted in a shorter cannula-to-herniation distance ($P < 0.05$) and lower postoperative back pain VAS scores ($P = 0.0004$), with no cases of dysesthesia. There were no significant differences in leg pain VAS, ODI, re-herniation, or reoperation rates between groups. Conclusions: The centrifuge trephine system demonstrated superior accuracy and efficiency compared to the conventional trephine, and was associated with improved clinical outcomes. It may be an alternative to conventional foraminoplasty techniques in TELD procedures.

Keywords: Spine surgery, endoscopic discectomy, foraminoplasty, centrifuge trephine, minimally invasive spine surgery, cannula positioning

Introduction

Lumbar disc herniation (LDH) is a common degenerative spinal disorder that frequently causes low back and leg pain [1-3]. In recent years, percutaneous transforaminal endoscopic lumbar discectomy (TELD) has gained widespread acceptance as a minimally invasive surgical technique because of its advantages of reduced tissue trauma, faster recovery, and shorter hospital stay [4-7]. Among the advances in minimally invasive spine surgery (MISS), TELD has emerged as one of the most widely adopted techniques for the management of LDH over the past two decades [8-10]. Its advantages are largely attributed to the preservation of paraspinal muscles and bony structures, resulting in less postoperative back pain and faster functional recovery [5, 11].

A key step in TELD is foraminoplasty, a facet osteotomy performed at the Kambin's triangle to create an adequate working channel and optimize the approach angle for disc removal [12-14]. Following foraminoplasty, the working cannula can be accurately positioned to enable effective decompression of the herniated disc [13]. The accuracy of this process is crucial for minimizing surgical trauma and improving clinical outcome [11, 15, 16].

Traditionally, foraminoplasty has been performed using a series of trephines with progressively increasing diameters [9]. However, this method is often associated with prolonged fluoroscopy exposure, limited control over cannula trajectory, and a relatively steep learning curve, particularly for less experienced surgeons [12]. Although modified foraminoplasty techniques

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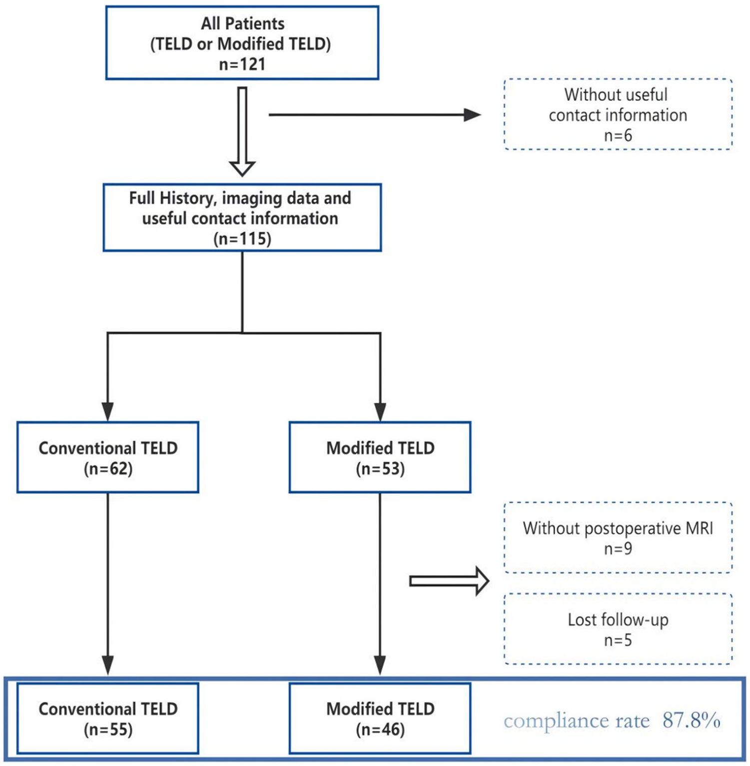

Figure 1. Follow-up flow in two groups.

have been proposed to improve procedural efficiency [8, 17], currently available trephine systems still lack the capability to simultaneously adjust the guiding rod position, perform precise osteotomy, and ensure accurate cannula placement. To overcome these limitations, we developed a novel centrifuge trephine system designed to improve the precision, efficiency, and controllability of foraminoplasty. This study aimed to evaluate the performance of this system through both laboratory simulations and clinical applications.

Materials and methods

Indications

TELD was indicated for patients with symptomatic single-level lumbar disc herniation who failed at least 6 weeks of conservative treatment, presented with radicular pain or neurological deficits, and had imaging findings consistent with nerve root compression.

Patients

This study consisted of a laboratory simulation and a retrospective clinical evaluation. One hundred and twenty-one patients underwent TELD for single-level lumbar disc herniation from Jan 2018 to Jan 2022 (**Figure 1**).

Inclusion criteria: (1) Single-level lumbar disc herniation; (2) Age from twenty to eighty; (3) Suffering from conventional TELD or Modified TELD in these three centers (Shanghai Changzheng hospital, Navy 905th Hospital and Tongren hospital); (4) The contained disc herniation, the extruded disc herniation, the sequestered disc herniation and the near-migrated disc herniation (zones 2 and 3) in the lumbar spine [18].

Exclusion criteria: (1) A history of previous spine surgery; (2) Multilevel disc herniation; (3) TELD surgery beyond the L3/4, L4/5 or L5/S1 level; (4) Insufficient medical records and follow-up data during the scheduled 1-year period; (5) Death or other disease which caused the failure of follow-up; (6) A history of neurological diseases.

This was a retrospective study. Patients were assigned to the standard TELD group or the modified TELD group according to the surgical technique used at the time of operation, based on the surgeon's assessment of anatomic features (e.g., foraminal diameter, facet hypertrophy) and patient preference. No randomization was performed. Baseline demographic and clinical variables (age, sex, surgical level, preoperative VAS and ODI scores) were comparable between groups (all $P > 0.05$), minimizing the potential for selection bias.

Surgical techniques

All surgeries were performed by two spine surgeons with over 5 years of TELD experience. The distribution of surgeries between surgeons was balanced between groups to minimize operator-dependent bias.

Local anesthesia was performed with the patient in the prone position on a radiolucent

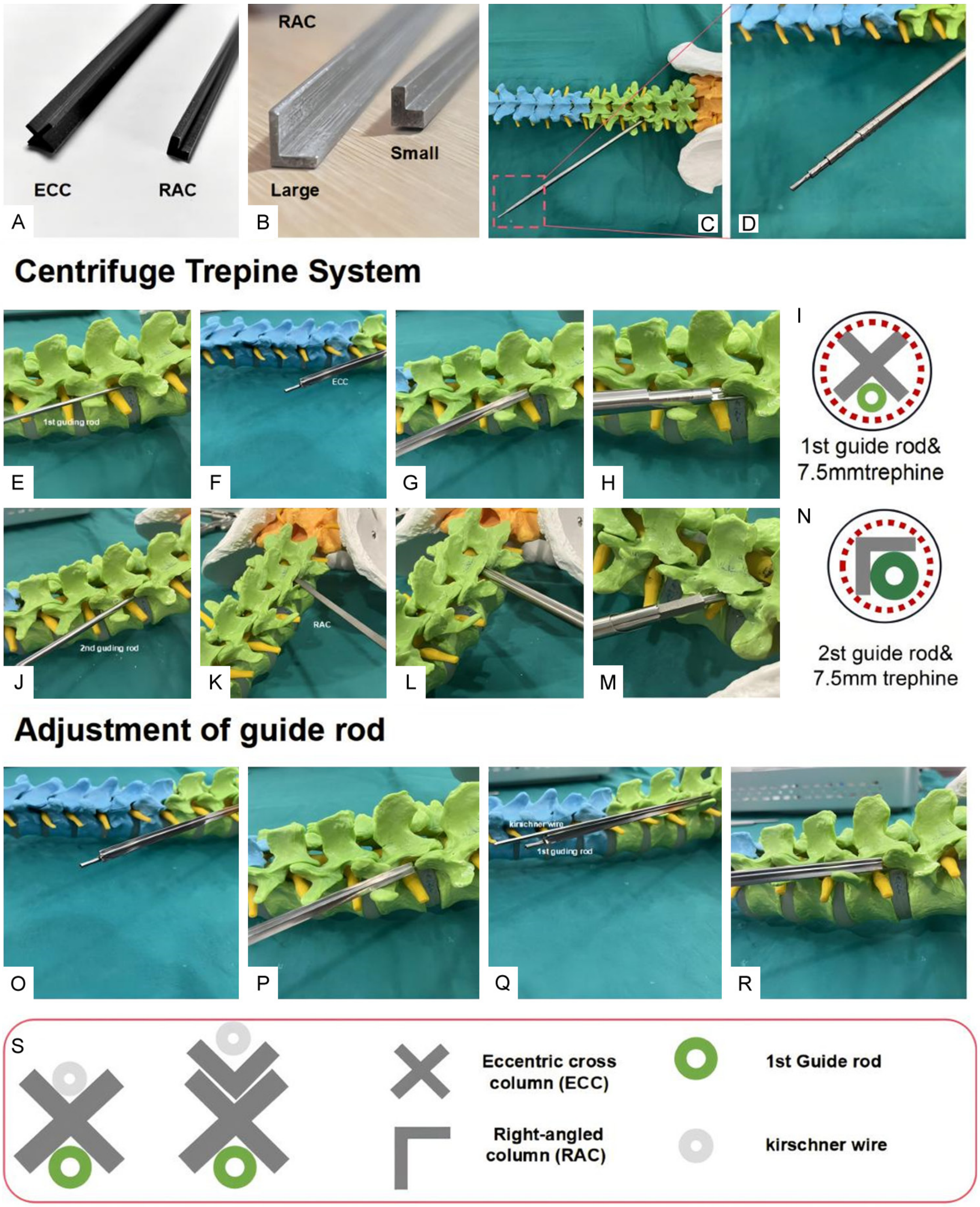

Figure 2. Centrifuge trephine system. A, B. Photos of the right-angled column (RAC) and eccentric cross column (ECC). C, D. The process of dilation cannula. E-H, J-M. Application of the centrifuge trephine system in the 3D print model. I, N. Schematic drawing of ECC and RAC. O-R. Adjustment of guiding rod by ECC. S. Schematic drawing of adjustment of the guiding rod by ECC.

table after verifying the surgical segment by fluoroscopy and drafting marker lines. (1) The puncture needle's position was checked after entering the skin. (2) Adjusting the puncture needle to a suitable position, sequential dilated pipelines were used to dilate the soft tissue, including the muscle and fascia. (3) The techniques of foraminoplasty are described below

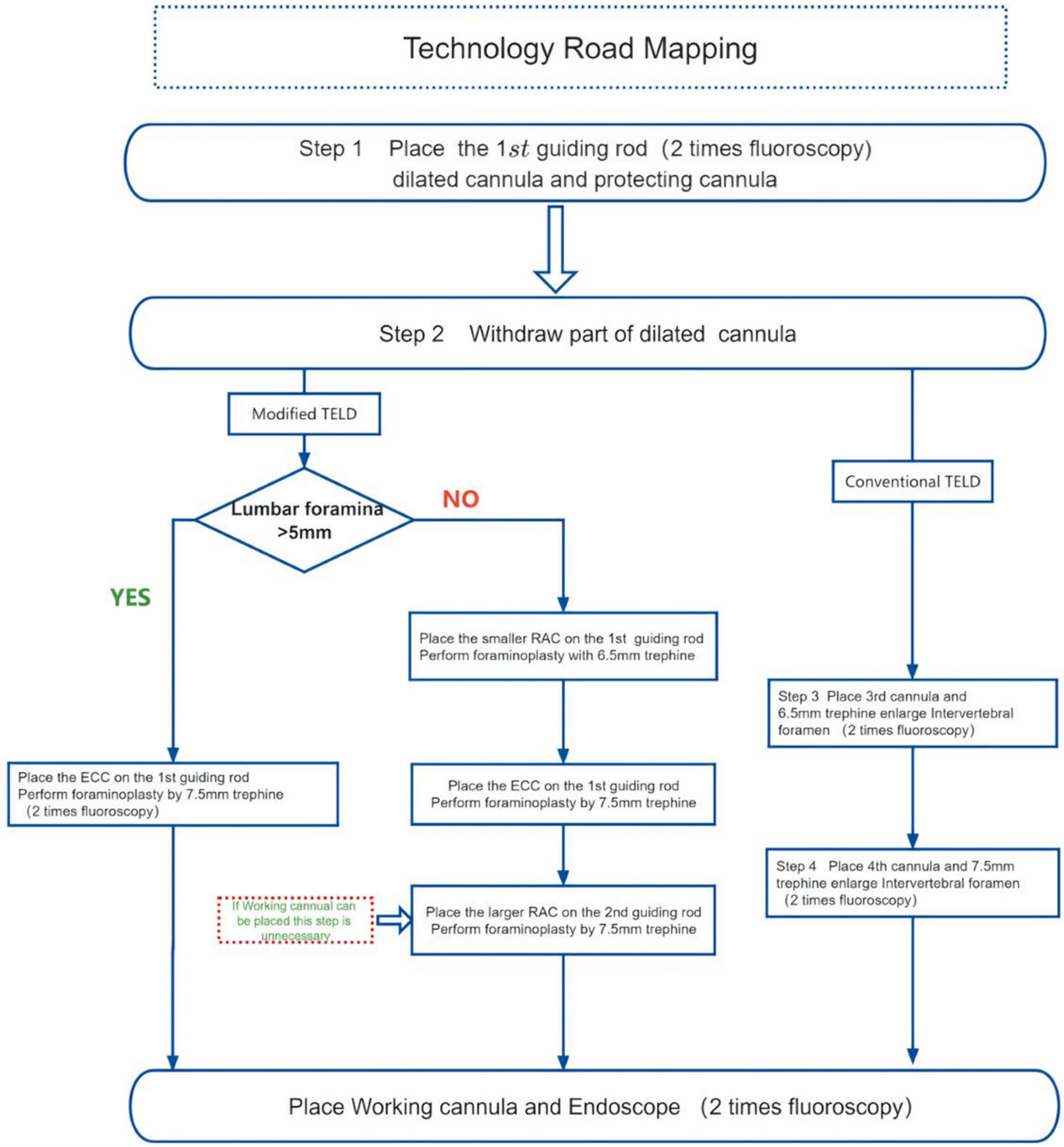

Figure 3. Work flow of trephine system.

in two ways (**Figure 3**). (4) The 'targeted discectomy' was performed efficiently for adequate nerve decompression [10, 17].

Foraminoplasty with centrifuge trephine system

The newly designed centrifuge trephine system consists of an eccentric cross column (ECC) and a right-angled column (small and large RAC), as shown in **Figure 2A**, **2B**. (A) After dilation of the soft tissue was performed with pipelines (**Figure 2C**, **2D**), the guiding rod and protecting cannula were reserved (**Figure 2E-N**). (B) A 7.5 mm trephine was utilized in conjunction with an ECC and guiding rod to perform centrifugal foraminoplasty until working cannula can be correctly placed (**Figure 2H**, **2M**).

If the diameter of the foramen was estimated to be narrow (less than 5 mm), a 6.5 mm trephine was used on top of the small RAC and guiding rod to perform the foraminoplasty, followed by

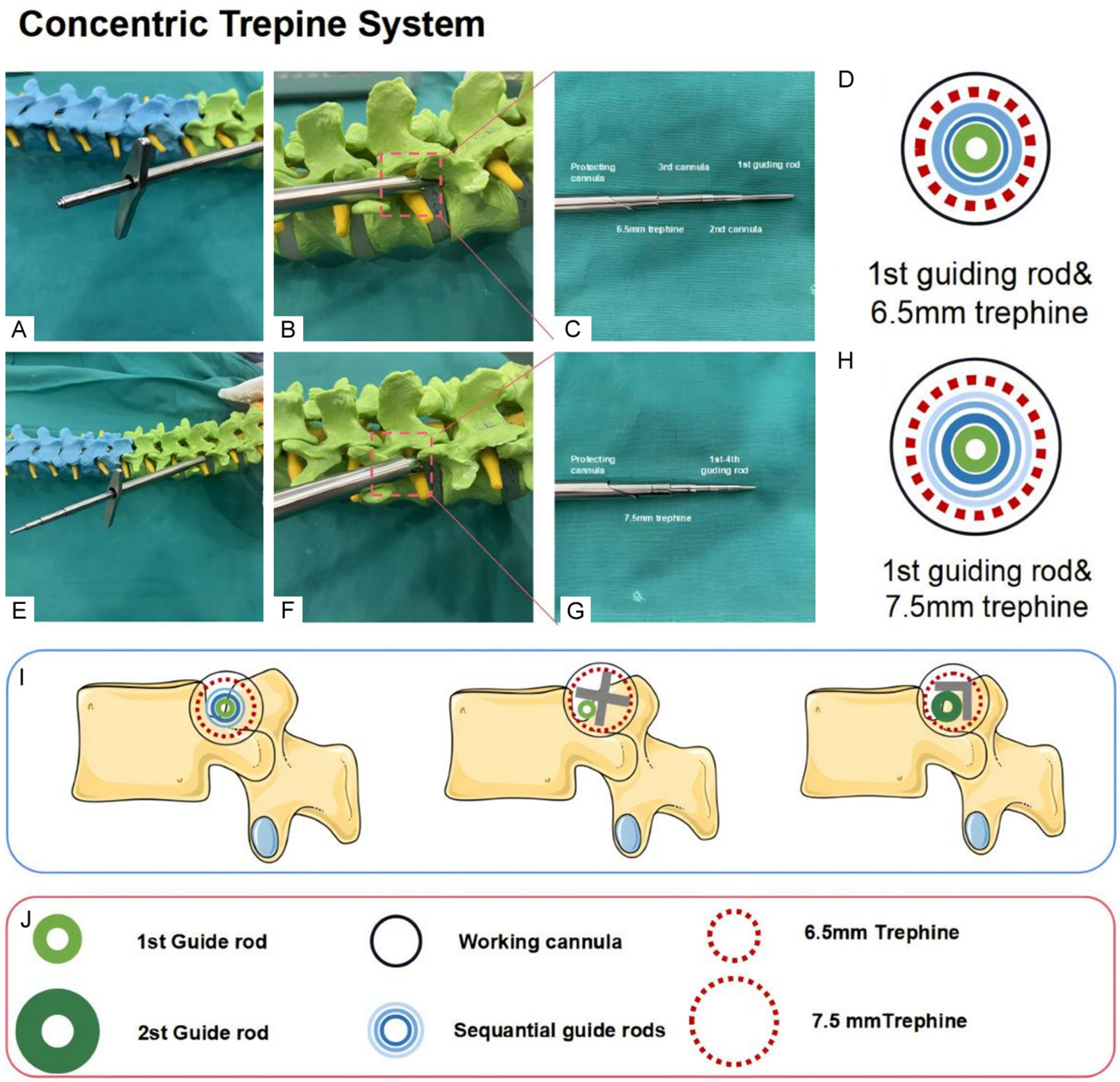

Figure 4. Concentric trephine system. (A-E) First step of conventional foraminoplasty with 6.5 mm trephine; (E-G) Second step of conventional foraminoplasty with 7.5 mm trephine; (I) Range of foraminoplasty in conventional transforaminal endoscopic lumbar discectomy (TELD) and modified TELD; (J) Legend of (D) and (H).

further foraminoplasty by a 7.5 mm trephine with ECC.

The ECC can also be used as an offset to change the position of the guiding rod. The ECC could be inserted along the 1st guiding rod in the direction of which it needs to change (**Figure 2O-R**). Then, another guiding rod was inserted into the rail of the ECC, which pointed to the right position (**Figure 2Q**, **2R**). In addition, there were still different compound modes among the 1st and 2nd guiding rods, ECC, and RAC. The demonstration figures are shown in **Figure 2I**, **2N** and **2S**.

The main function of the Centrifuge Trephine System was to adjust the rod position and enlarge the rim of the foraminoplasty (**Figure 2**). Foraminoplasty could be more precisely performed towards the tip of the superior articular process (SAP) rather than the bone of the vertebrae (**Figure 4I**).

Foraminoplasty by the traditional process

(A) The soft tissue was dilated by sequential pipelines. (B) The 6.5 mm trephine and protecting cannula were placed through the 3rd dilated pipeline, and the position was checked before foraminoplasty (**Figure 4A-D**). (C) Subsequently, the 4th dilated pipeline was put in, and the 7.5 mm trephine was checked again by C-arm fluoroscopy system before foraminoplasty (**Figure 4E-H**). If the foramen was large enough, the working cannula was entered.

If the inner side of the foramen was not large enough, further foraminoplasty was performed. The 2nd guiding rod was entered more flatly and deeply attached to the SAP. The 3rd and 4th dilated pipelines and protecting cannula were put through. Then, a 7.5 mm trephine was used to enlarge the foramen. The inner rim of the SAP was removed until the guiding rod could pass the medial line of the pedicles freely. Finally, the working cannula was entered.

Laboratory test

A dedicated laboratory setup was established for experimental validation, equipped with a C-arm fluoroscopy unit (KD-C51110, Shanghai Electric, China) integrated with a spinal navigation and positioning system (JA-SN001, Keyinbot®, China). This system enabled precise measurement of three-dimensional distances the tip of the working cannula and the simulated herniation site, thereby allowing an objective evaluation of foraminoplasty accuracy.

Life-size (1:1 scale) lumbar spine models were fabricated using high-resolution 3D printing based on anonymized CT datasets from actual patients. The bone density of the models was calibrated to simulate the mechanical properties of both cortical and cancellous bone.

A total of 30 TELD simulation procedures were performed using either the conventional or the centrifuge trephine system. All procedures were randomized and conducted under identical environmental and technical conditions. Outcome measurements - including operative time, number of fluoroscopic images, and the final cannula-to-herniation distance were recorded by three independent evaluators who were blinded to group allocation. Inter-rater reliability was assessed to ensure consistency of the measurements.

Outcome assessment

Postoperative follow-up was conducted at 1 month, 6 months, and 1 year in outpatient clinics. At the 1-year follow-up, all patients underwent both MRI and plain radiographs. Clinical data were retrospectively collected from medical records, including the surgical level, operative time, intraoperative fluoroscopy frequency, and the distance between the final position of the working cannula and the center of the herniated disc, as measured intraoperatively using a specialized C-arm system equipped with spinal navigation.

Clinical outcomes were assessed using the Oswestry Disability Index (ODI) and Visual Analogue Scale (VAS) scores for back and leg pain at baseline and at the 1-year follow-up. The ODI was measured with the standard 10-item questionnaire, each item scored from 0 to 5, and the total score expressed as a percentage of disability (0% = no disability, 100% = maximum disability). The VAS for both back and leg pain was recorded using a 10-cm horizontal line, where 0 indicated no pain and 10 indicated the worst imaginable pain. Reoperation at the index level within 1 year was recorded. Re-herniation was defined as recurrence of ipsilateral radicular symptoms with at least a 3-point increase in leg VAS score and radiological evidence of recurrent herniation at the same disc level [19]. All data were independently collected and verified by three trained investigators.

Statistical analysis

Statistical analyses were performed using SPSS software (version 25.0; SPSS Inc., Chicago, IL). Normally distributed data were presented as mean ± standard deviation (SD), while non-normally distributed data were expressed as median with interquartile range (IQR). Between-group comparisons were conducted using the Mann-Whitney U test for continuous variables and the chi-square test or Fisher's exact test for categorical variables. A p-value < 0.05 was considered significant.

Results

Laboratory test

In the laboratory simulation, the operation duration, number of fluoroscopic shots, and cannula-herniation distance were compared between the modified and conventional groups. The modified group showed a significantly shorter operative time (t = 3.33, $P < 0.001$) and lower fluoroscopic exposure (t = 4.85, $P < 0.001$) compared to the conventional group. Notably, the number of fluoroscopic images required in the modified group was approximately half that of the conventional group (**Figures 5** and **6**). However, no significant difference was observed in the cannula-herniation distance between the two groups (t = -0.51, P = 0.508) (**Table 1**).

Clinical application

Patient demographics: Out of 121 enrolled patients, 6 were lost due to invalid contact information, and 14 were excluded due to missing postoperative MRI or outpatient records. A total of 101 patients (64 males and 37 females; mean age 35.97 ± 15.18 years) completed the full 1-year follow-up, yielding a compliance rate of 87.8% (**Figure 1**). Baseline demographic and clinical characteristics - including age, sex, surgical level, preoperative VAS, and ODI - were comparable between the modified and conventional groups ($\chi^2 = 1.21$ for sex distribution, all $P > 0.05$) (**Table 2**).

Clinical outcomes: The modified group had a significantly shorter operative time (52.3 ± 7.45 minutes) compared to the conventional group (59.5 ± 13.55 minutes; t = 2.88, P = 0.0052). Similarly, intraoperative fluoroscopic usage was significantly reduced in the modified group (t = 4.72, $P < 0.0001$) (**Table 3**).

The mean cannula-to-herniation distance was significantly shorter in the modified group (5.52 ± 2.99 mm) than in the conventional group (6.91 ± 3.79 mm; t = 2.07, P = 0.043), indicating greater accuracy of cannula placement. The incidence of postoperative dysesthesia was 3.7% in the conventional group, whereas no cases were reported in the modified group ($\chi^2 = 0.46$, P = 0.496).

Low back pain VAS scores at one-year follow-up were significantly lower in the modified group (1.10 ± 1.09) compared to the conventional group (2.24 ± 0.87; t = 3.85, P = 0.0004). However, no significant differences were observed in leg pain VAS (t = 0.13, P = 0.894) or ODI scores (t = 0.21, P = 0.836) between groups.

No patient in either group required reoperation during the follow-up period. The re-herniation rates were also comparable between groups ($P > 0.9999$).

Discussion

We demonstrated that a newly developed centrifuge trephine system significantly improves the efficiency and precision of foraminoplasty in TELD, while simultaneously minimizing radiation exposure and shortening operative time. These advantages were consistently observed across both laboratory simulations and clinical applications, underscoring the reproducibility and robustness of the findings. Compared to conventional concentric trephine systems, the centrifuge trephine provides a more versatile and ergonomic design, allowing precise trajectory adjustment and potentially lowering the risk of iatrogenic nerve or dural injury. In our view, unlike conventional concentric systems that rely on repeated repositioning, the eccentric modular design permits real-time, dynamic trajectory adjustment and facilitates “individualized” foraminoplasty strategies tailored to each patient’s anatomy. This flexibility may help flatten the learning curve for less experienced surgeons and expand the indications of TELD to anatomically challenging levels such as L5/S1.

Foraminoplasty remains the critical step in TELD, as precise placement of the working cannula at the optimal entry zone is essential for effective neural decompression and symptom relief. Foraminoplasty is technically demanding, requiring meticulous preoperative planning and precise intraoperative trajectory control under fluoroscopic guidance. The main challenges include: (1) Trajectory control - the working cannula must be inserted at an optimal angle to reach the target disc space while avoiding injury to the exiting nerve root. Limited control over trajectory often necessitates repeated adjustments. (2) Risk of neural or dural injury - during bone removal and cannula placement, the exiting nerve root and dura are vulnerable to mechanical or thermal damage. (3) Prolonged fluoroscopy exposure - multiple trajectory adjustments increase fluoroscopy time, leading to higher radiation exposure for both patients and surgical staff. (4) Steep learning curve - foraminoplasty requires familiarity with endoscopic anatomy and precise spatial orientation, making it technically

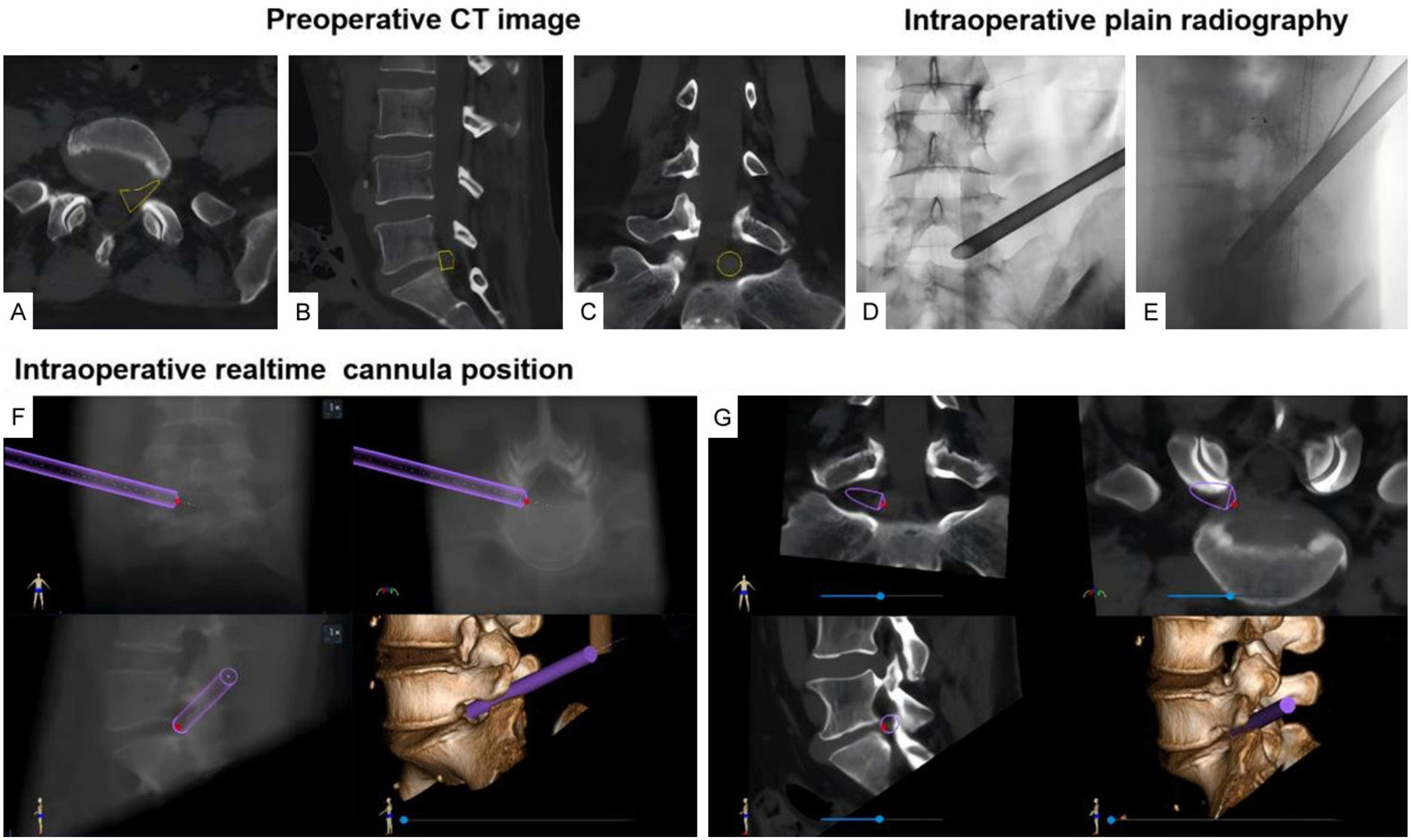

Figure 5. Working principle of the spinal surgery navigation and positioning system in measuring distance. A-C. Preoperative CT images showing the target intervertebral foramen and planned working channel trajectory in axial, sagittal, and coronal planes. D, E. Intraoperative plain radiographs confirming the initial trajectory of the guiding needle and working cannula placement. F, G. Real-time intraoperative navigation display demonstrating the virtual trajectory of the working cannula in multiple planes and 3D reconstruction.

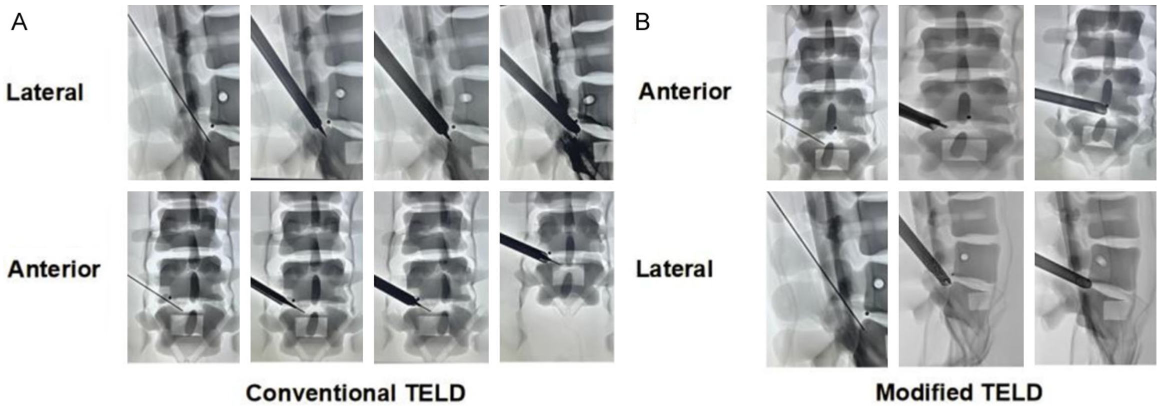

Figure 6. Intraoperative foraminoplasty during operation in the two groups. A. Intraoperative foraminoplasty of conventional TELD. B. Intraoperative foraminoplasty of modified TELD.

Table 1. Laboratory test data

	Conventional group	Modified group	t value	*P* value
Operative time (min)	24.23 ± 7.06	16.77 ± 5.05	3.33	< 0.001
Fluoroscopic times (times)	9 (1.0)#	7 (1.125)#	-	< 0.0001
Distance (mm)	10.62 ± 2.76	11.12 ± 2.61	-0.51	0.508

Distance: the distance between the working cannula and the hypothetic herniation (Cannula-herniation). #: these data were expressed by median (interquartile range).

Table 2. Demographic data comparison between the two groups

Group		Total	Conventional group	Centrifuge group	χ^2 value/*P* value
n		101	55	46	-
Mean age (years)		35.97 ± 15.18	38.45 ± 15.22	33.00 ± 14.75	> 0.05
Male/Female		64/37	38/17	26/20	χ^2 = 1.21, P > 0.05
Surgical segment	L3/4	3	2	1	> 0.05
	L4/5	51	29	22	
	L5/S1	47	24	23	
VAS (low back pain)		3.34 ± 2.17	3.42 ± 2.20	3.17 ± 2.18	> 0.05
VAS (leg pain)		5.50 ± 2.81	5.66 ± 2.59	5.33 ± 3.08	> 0.05
ODI (%)		39.68 ± 14.47	39.20 ± 13.78	40.16 ± 15.40	> 0.05

demanding, particularly for less experienced surgeons [10, 20].

Several modified techniques have been proposed to overcome these challenges. For instance, Li et al. introduced a duckbill-shaped protective cannula to shield the exiting nerve root and improve trephine stability [12]. However, its long tip may cause nerve irritation, particularly at the L5/S1 level, and has been associated with postoperative dysesthesia in some cases. In contrast, no dysesthesia occurred in our modified group, suggesting that the centrifuge trephine system may offer a safer alternative, particularly in anatomically constrained levels such as L5/S1. This system allows multi-axial adjustment and modular assembly, resembling a "LEGO-brick" design, which facilitates highly individualized foraminoplasty strategies tailored to specific anatomic requirements. For example, when decompression of the lateral recess is required, the centrifuge design allows a dorsal shift of the trephine path to avoid vertebral body damage while effectively removing the superior articular process tip - an approach difficult to achieve with concentric systems.

Another key innovation lies in its adaptability to challenging cases with a narrow foramen (< 5

Table 3. Analysis of clinical follow-up data

	Conventional group	Modified group	t value	*P* value
ODI (%)	12.33 ± 2.81	13.55 ± 2.34	0.21	P = 0.8357
VAS (low back pain)	2.24 ± 0.87	1.10 ± 1.09	3.85	P = 0.0004*
VAS (leg pain)	0.50 ± 0.93	0.45 ± 0.77	0.13	P = 0.8939
Dysesthesia (n)	2 (3.6%)	0	-	P = 0.4961
Operative time (min)	59.5 ± 13.55	52.3 ± 7.45	2.88	P = 0.0052
Fluoroscopic times (times)	12.5 (3)#	7.5 (2.75)#	-	P < 0.0001*
Distance (mm)	6.91 ± 3.79	5.52 ± 2.99	2.07	P = 0.0429*
Re-herniation (n)	1 (1.8%)	2 (4.3%)	-	P = 0.5901
Re-operation rate (n)	0	0	-	P > 0.9999

Distance: the distance between the working cannula and the herniation (Cannula-herniation). #: these data were expressed by median (interquartile range). *: P<0.05.

mm) or hypertrophic facets. By elevating a second guiding rod toward the spinal canal axis, the surgeon can expand the resection field in a controlled and predictable manner, potentially reducing the need for high-speed burr usage and thereby minimizing thermal injury risk. This feature is particularly relevant for the future integration of robotic or navigation-assisted TELD, where precise trajectory planning and accuracy are essential.

Interestingly, although no significant difference in cannula-to-herniation distance was observed in the laboratory models, the clinical outcomes clearly favored the modified system. This discrepancy may be attributed to differences in the material properties of 3D-printed bones and the idealized visual feedback in the laboratory environment. In real surgical scenarios, soft tissue handling, bleeding, and limited visualization likely make the advantages of precise trajectory control more pronounced.

Postoperative low back pain remains a common complaint after TELD [21]. Previous studies have reported varying degrees of residual pain, which are likely related to annular or facet injury sustained during foraminoplasty [22, 23]. In our study, the modified group reported significantly lower back pain scores, which we believe is not merely statistically significant but also clinically meaningful, as it reflects reduced trauma to stabilizing structures such as the facet joint and annulus fibrosus. The system's ability to "walk" closer to the herniated fragment enables more efficient discectomy with less mechanical disruption of surrounding tissues.

Taken together, the centrifuge trephine system introduces several novel features - including multi-directional control, modular assembly, and trajectory optimization - that address long-standing limitations of conventional foraminoplasty tools. Our findings support the centrifuge trephine system as a promising alternative to conventional foraminoplasty. We contend that its multi-directional control and modular design may lay the groundwork for seamless integration with navigation or robotic platforms, representing a step toward more intelligent, personalized, and precise TELD procedures.

Conclusion

The centrifuge trephine system demonstrated clear advantages over the conventional system, including reduced operative time, fewer fluoroscopic exposures, improved cannula placement accuracy, and lower postoperative back pain. These findings suggest that the modified technique may serve as a more efficient and precise alternative in TELD. Further large-scale, long-term studies are warranted to confirm its clinical value and broader applicability.

Limitations and future directions

This study had several limitations. First, the clinical sample size was relatively small and from a single center, limiting the generalizability of the findings. Second, although laboratory testing was included, 3D-printed spine models cannot fully replicate the biomechanical and anatomic complexity of live tissue, particularly soft tissue behavior and bleeding. Third, all procedures were performed by experienced surgeons, and the learning curve for less experienced users was not evaluated.

Future studies should include larger, multi-center trials and assess the system's usability across different skill levels. Integration with navigation or robotic platforms may further enhance accuracy and reduce radiation exposure. Additionally, longer-term follow-up and application in more complex pathologies could broaden its clinical utility.

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Disclosure of conflict of interest

None.

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