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Original Article

The learning curve of a dynamic navigation system used in endodontic apical surgery

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Abstract *Background/purpose:* Quantitative *in vitro* research was conducted on the learning process of a dynamic navigation system. This study provides guidance for the promotion and application of dynamic navigation technology in the endodontic apical surgery field.
Materials and methods: Standardized models were designed and 3D printed to form the approach operation of endodontic apical surgery. 6 clinicians with no experience in dynamic navigation performed the operation. The distance deviation tolerance was set as 0.6 mm, and the angle deviation tolerance was set as 5°. Fifteen mm deep approach operation was completed using dynamic navigation. Each operator performed 10 consecutive exercises on the models. The positioning deviation and operation time of each operator for each practice were recorded. Based on this, the learning curve of the dynamic navigation of every operator was mapped. The learning difficulty of dynamic navigation was evaluated.
Results: The learning curves of all operators reached a stable level after the 7th practice, which can ensure that the distance and angle deviations are maintained within the deviation tolerances (0.6 mm, 5°).

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Conclusion: Operators with no experience in dynamic navigation technology need practice to master dynamic navigation operations. For this navigation system, operators with no operational experience can master dynamic navigation operations after 7 exercises.

Introduction

Endodontic apical surgery is an important method to preserve affected teeth.[1,2] Endodontic apical microsurgery has a higher success rate than traditional endodontic apical surgery and is currently widely used by dentists.[3] However, the effect of endodontic apical microsurgery highly depends on the surgeon's experience, and young doctors require a long learning process for performing endodontic apical surgery, so they have difficulty performing complex surgeries in their early career stages.[4]

As a new personalized digital medical technology, dynamic navigation enables real-time localization of a moving target by measuring parameters related to the position of the target, and correctly guides the target to its destination along a predetermined route from the point of departure.[5–7] Studies have shown that applying dynamic navigation in maxillofacial surgery can reduce the dependence on operation experience, improve surgical precision, and reduce the risks and difficulty of surgery.[8–10]

Recently, the applications of dynamic navigation in the stomatology field have gradually shifted from operating room to chair-side operations.[11–13] However, in applications of dynamic navigation in the same treatment, the accuracy achieved varies widely among different studies.[14–16] Possible reasons include the fact that the anatomical structures to be localized were not standardized across different studies and that the experience of operators varied across different studies. Applications of dynamic navigation in endodontic apical surgery are often discussed in case reports.[17–20] Investigation of the learning curve is of great significance for promoting the dynamic navigation in endodontic apical surgery. However, to our knowledge, the learning difficulty of its application in endodontic apical surgery has not been reported, and no research has been conducted to instruct the learning of dynamic navigation in endodontic apical surgery.

To address the above problems, a standardized model for accurately evaluating the dynamic navigation used in endodontic apical surgery was designed in this study. The learning curve of dynamic navigation was drawn, providing a reference for the promotion of dynamic navigation technology.

Materials and methods

Computer-aided design and 3D printing standard models

A standardized model for evaluation of operation accuracy using dynamic navigation in endodontic apical surgery was designed using Rhino 7 software (McNeel, Seattle, WA, USA). Referring to a related study, the sample size for a single experimenter was set as 10.[16] We designed a cube that can accommodate 15 mm-deep hemispherical cavities as simulated apical lesions with intact cortical bone in endodontic apical surgery. Each hemispherical cavity has a diameter of 5 mm to accommodate our chosen 4.5 mm diameter trephine (Changsha Tiantian, Changsha, China).

The data of the model were exported in stereolithography (STL) format and printed using an Objet30 Prime printer (Stratasys, Eden Prairie, MN, USA) in glossy mode with VeroClear resin (Stratasys).

Access planning

Silicone rubber impression material (HUGE, Shanghai, China) was used to fix the alignment device into the reserved groove on the model. Then, the model was scanned with cone beam computed tomography (CBCT, New Tom VGi, QR Corporation, Verona, Italy; layer thickness 125 μm, FOV 8 × 8 cm, 110 kV, 4.00 mA). The CBCT data saved in DICOM format were imported into the dynamic navigation system (DCARER, Suzhou, China). An implant with the same diameter as the trephine was selected in the software for the access design.

The planned trephine position was achieved by adjusting the implant in the sagittal and axial planes according to the following criteria: (1) the frontmost part of the implant reached the front of the hemisphere; (2) the angle between the implant and the outer surface of the model was set to 90°.

The handpiece was calibrated into the dynamic navigation system (Fig. 1A). The reference plate was connected to the model through a fixation device (Fig. 1B). The calibrated handpiece was used to match the model with the CBCT data through the alignment device (Fig. 1C).

Learning process of dynamic navigation

Six endodontics residents with no experience in dynamic navigation were selected as operators. 0.6 mm-5° was set as the maximum distance-angle deviation tolerance. When the screen showed that the distance or angle deviation was greater than the set tolerance, the operators must immediately stop and correct the operation (Fig. 1D and E). The operators must stop drilling any deeper when the indicated depth reached 0.0 mm.

According to a research on learning difficulty of dynamic navigation,[21] each operator performed 10 consecutive learning sessions. For each operator per operation learning, the time from the start of drilling to the completion of the entry was recorded.

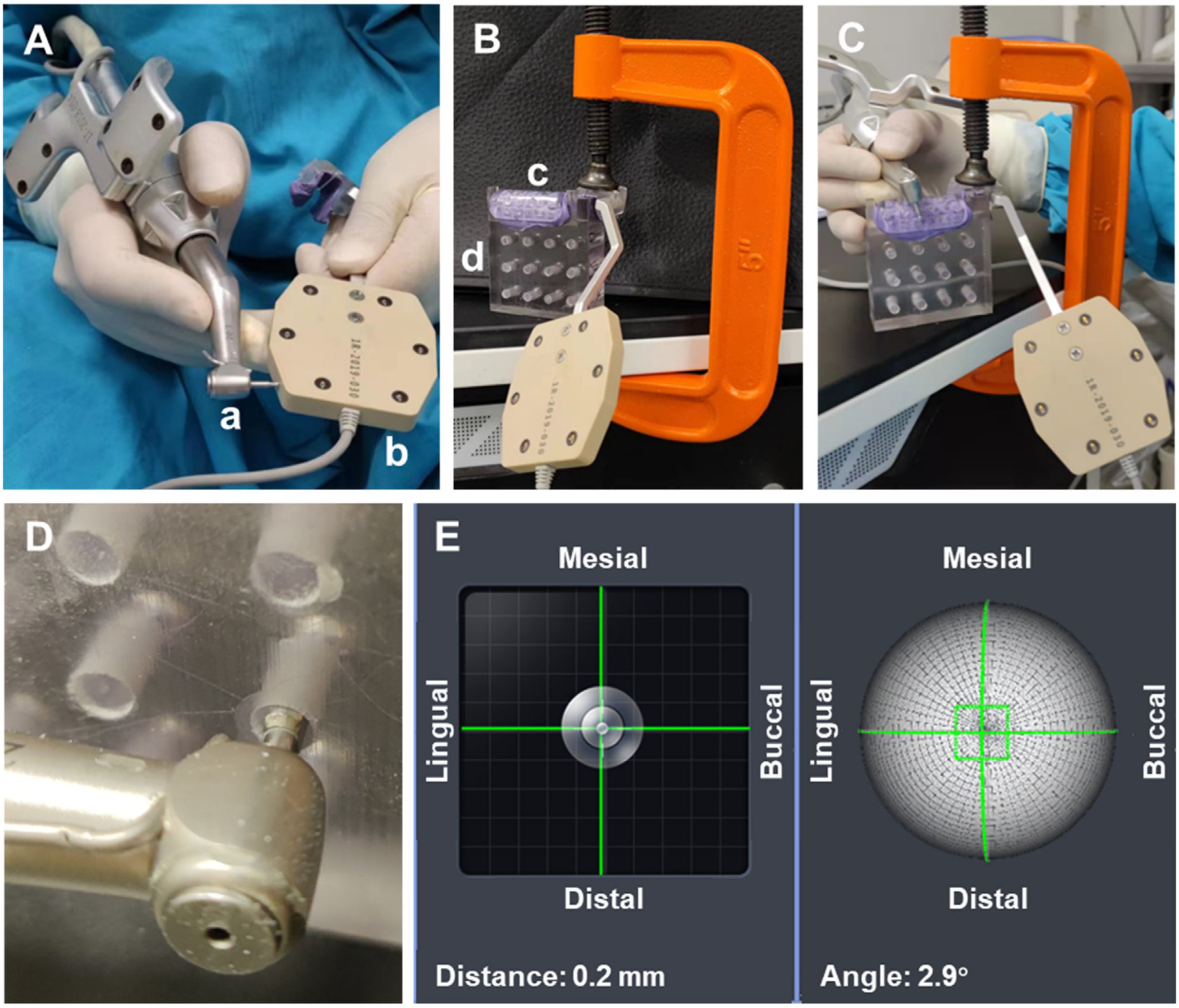

Figure 1 The surgical procedure under the dynamic navigation. (A) The handpiece was calibrated into the dynamic navigation system through the reference plate. (a) The handpiece, (b) the reference plate. (B) The alignment device was fixed on the model using silicone rubber impression material, the model was fixed on a table, and the reference plate was fixed on the model. (c) The alignment device, (d) the model. (C) The calibrated handpiece was used to match the model with the CBCT data through the alignment device. (D) The access operation under the dynamic navigation. (E) The distance and angle deviation displayed by the dynamic navigation system.

An evaluator evaluated the effectiveness of each operator during the access operation. The evaluation index was divided into two aspects as follows.

Positioning accuracy: The evaluator recorded the magnitude of the distance and angle deviation displayed by the navigation system for every 1 mm of depth during the operation.

Operation efficiency: The evaluator recorded the time needed to reach the target position from the start of drilling.

Drafting the learning curve for dynamic navigation technology

Postoperative CBCT was performed according to the preoperative conditions. The DICOM data were imported into MIMICS 21 (Materialise, Glen Burnie, MD, USA) to reconstruct the postoperative models. The access for each approach was fitted by an evaluator in Geomagic Control software (Geomagic, Morrisville, NC, USA) based on the reconstructed models. The deviations between the planned and actual access were evaluated. The 2D distance deviation (horizontal projection of the distance deviation between the actual and planned path at the deepest point), 3D distance deviation, depth deviation, angle deviation, and initial position deviation were calculated according to the previous literature.[9,22]

The learning curves were drafted according to postoperative analysis and intraoperative observations: (1) the variation in the 2D distance deviation, 3D distance deviation, depth deviation, angle deviation, initial position deviation and operation time for each operation of the 6 operators; (2) the distance and angle deviation displayed by the navigation system in real time for every 1 mm depth during each operation of the 6 operators.

Results

The learning curve of the variation for each index of the 6 operators is shown in Fig. 2. The 2D distance deviation, 3D distance deviation, depth deviation, angle deviation and operation time using dynamic navigation gradually decreased with the increase of practice times and leveled off at the end of the learning curve. After learning and practicing on the models for endodontic apical surgery, the accuracy exhibited by the 6 operators was close. The results showed that the 6 operators achieved smoother curves after different numbers of practice sessions, and all operators reached smooth curves in each evaluation index after the 7th practice session.

The results of this study show that different operators have different learning speeds and styles, and therefore, each operator has a different learning curve. Operator 1 and Operator 3 had the highest 3D distance deviations among all operators. Operator 1 exhibited a significantly higher maximum depth deviation than the others in the 2nd practice. However, the positioning deviations of Operator 1 and Operator 3 decreased significantly with the increase of practice times. For example, the 3D distance deviation of Operator 1 decreased from 0.83 mm to 0.56 mm, and that of Operator 3 decreased from 0.87 mm to 0.50 mm. The positioning deviation of Operator 2 fluctuated greatly for the first five practices and leveled off after the 7th practice. In addition, Operator 2's angle deviation was always within 3° except for that of the 2nd operation. However, this operator spent the most time among all operators to maintain a smaller angle deviation, and the time was significantly higher than that of the

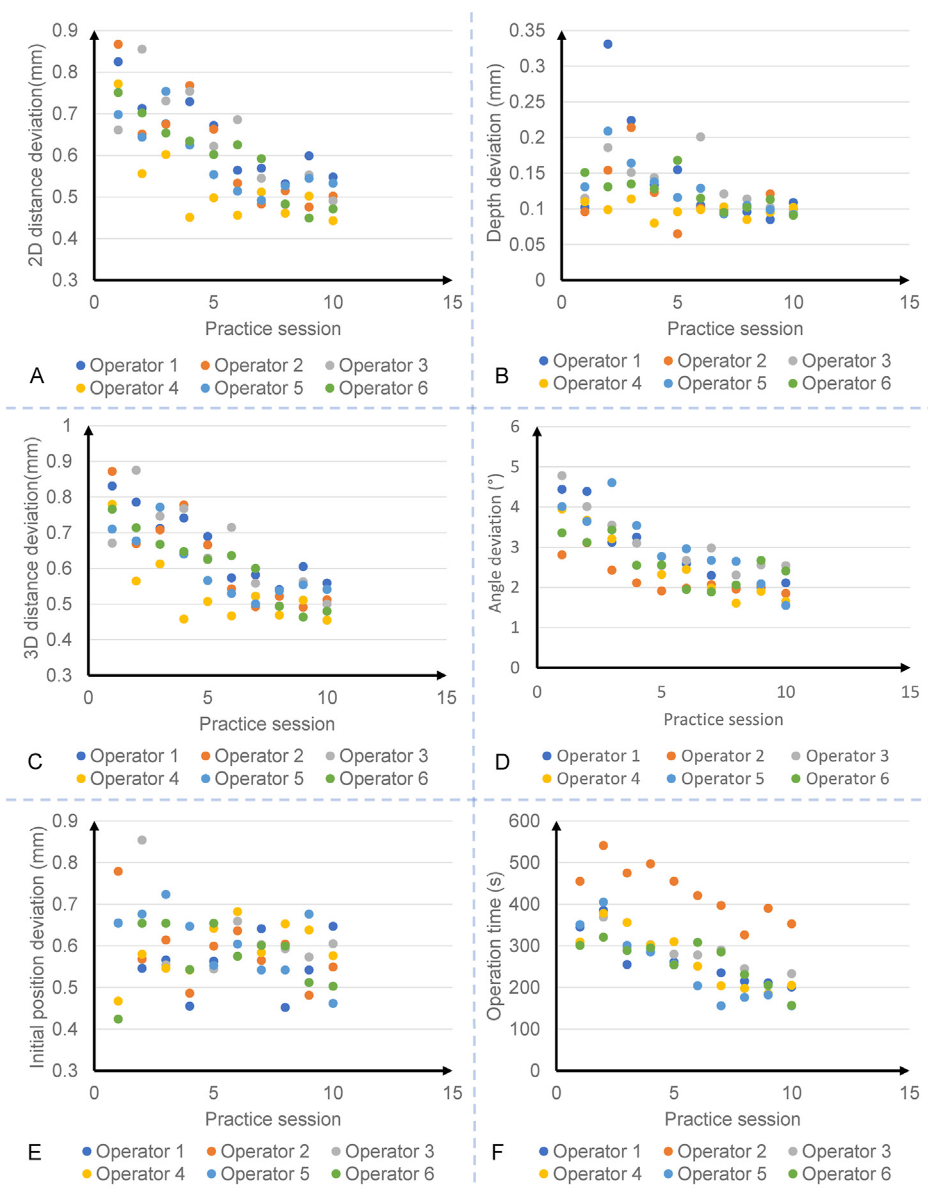

Figure 2 The learning curve of the variation for each index of the 6 operators using dynamic navigation. (A) 2D distance deviation, (B) Depth deviation, (C) 3D distance deviation, (D) Angle deviation, (E) Initial position deviation, (F) Operation time.

other operators. His pursuit of a smaller angle deviation did not make his 3D distance deviation smaller than that of the other operators. The positioning deviations of Operator 5 and Operator 6 decreased significantly as they continued practicing, and the curves leveled off after the 6th and 7th practice sessions. Operator 4 was the most rapid learner and could control the 3D distance deviation within 0.53 mm after the 4th operation. After the 7th operation, there were no significant differences between Operator 4 and the other operators, indicating that after learning, different operators had similar levels of mastery of dynamic navigation techniques.

The distance and angle deviation values displayed by the navigation system in real time for every 1 mm of depth of the trephine were recorded for each of the 6 operators during each operation. The dynamic navigation learning curve of each operator was plotted for the 1st, 3rd, 5th, 7th and 10th practice sessions (Fig. 3). The distance and angle deviation values displayed by the navigation system were within the deviation tolerances (0.6 mm, 5°) after the 7th practice. The deviation was always less than the deviation tolerances for the 8th to 10th exercises.

As the number of exercises increased, the positioning accuracy and operation time of the operators under dynamic navigation guidance were significantly optimized. The 3D distance deviation of all operators was analyzed for the 7th to 10th operation. One-way ANOVA was used to conduct intergroup analysis on the 6 operators ($F = 2.606$, $P = 0.061 > 0.05$). After the 7th exercise, the 3D distance deviation between different operators no longer exhibited significant differences.

Discussion

It is significant to study the learning curve of dynamic navigation technology. Unlike static guides restricting the direction and position of the drilling by mechanical structures,[23—26] dynamic navigation relies heavily on direct manipulation by the operator.[27] Operation under dynamic navigation guidance requires watching the screen while performing. A stable operation with dynamic navigation requires adequate practice to adapt to the unique operating posture and to the extra tracker weight on the handpiece.[28,29]

Previous studies have suggested a correlation between the mastery of dynamic navigation techniques and the number of practice sessions.[21,30,31] It was shown that students majoring in implantology with no experience in dynamic navigation exhibited significant reductions in positioning deviation and operation time after five sessions of training compared to their first sessions. Although the results showed that the learning curve of the operator's positioning accuracy leveled off after practice, the absolute value of the positioning deviation fluctuated between 1.5 mm and 2 mm.[31] This positioning deviation value is undoubtedly too large for endodontic apical surgery that requires a root-end resection of 3 mm. This result is because the deviation tolerance of the navigation was not limited, and the operator adjusted the implantation direction and angle only when the deviation was large. In fact, in this study, if the tolerances were set to 0.9 mm-7° (default tolerance of system), most of the inexperienced operators would be considered to have mastered the navigation technique after 2 to 3 practices. In our preliminary study, the influence of distance and angle deviation tolerance on the positioning accuracy of dynamic navigation was explored using 3D-printed models, which showed that the deviation tolerance suitable for endodontic apical surgery using dynamic navigation was recommended to be 0.6 mm-5°.

During the operation, the deviation tolerances were set as 0.6 mm-5°. It has been indicated that the positioning accuracy using dynamic navigation decreases as the drilling depth increases.[32] And a drilling depth of 5—15 mm can cover that of posterior tooth endodontic apical surgery.[33] Thus, a drilling depth of 15 mm was chosen to simulate one of the most difficult clinical situations. When an operator could maintain the positioning deviation within deviation tolerances (0.6 mm-5°) throughout the 15 mm drilling depth, and could continuously maintain this deviation in the three following experiments, the operator was considered to have initially mastered the dynamic navigation-guided operation on the models for endodontic apical surgery. The results showed that after the 7th practice, all operators were able to keep their deviations within the tolerance, as was the case in the subsequent three practices, and no significant differences were found between these operators and the skilled operators in our previous study.[32]

In this study, the actual postoperative trephine path was fitted in Geomagic Control software. The positioning accuracy was analyzed by comparing the deviation of the actual path with the planned path. 2D distance deviation, 3D distance deviation, depth deviation, angle deviation and initial position deviation were used as evaluation indexes. This is a commonly used method in the field of endodontic research on dynamic navigation.[9,22]

Each evaluation index has a corresponding practical clinical significance. For dynamic navigation-guided endodontic apical microsurgery, a smaller 2D distance deviation indicates a smaller positioning deviation in the proximal and distal directions, reducing the risk of damaging important anatomical structures such as adjacent tooth roots or mandibular canals. A smaller depth deviation indicates a smaller deviation in the penetration depth in the buccal and lingual directions, reducing the risk of damage to the palatal bone plate or injury to the maxillary sinus and reducing damage to healthy tissues during the surgical process. A smaller 3D distance deviation and angle deviation indicate that the surgical process is more accurate in locating and removing the root end and closer to the surgical target of vertically removing the root end by 3 mm. A smaller initial position deviation indicates a smaller positioning deviation on the bone surface, allowing the operator to accurately plan the surgical path and avoid mental foramen or uneven bone tissue on the surface of the buccal bone plate.

The learning curve for dynamic navigation was divided into two aspects in this study: intraoperative observation, which is deviation displayed by the dynamic navigation software, and postoperative analysis, which is deviation

Figure 3 Influence of learning times on the positioning accuracy of different drilling depths under the guidance of dynamic navigation. (A1, A2) Distance and angle deviation for operator 1, (B1, B2) Distance and angle deviation for operator 2, (C1, C2) Distance and angle deviation for operator 3, (D1, D2) Distance and angle deviation for operator 4, (E1, E2) Distance and angle deviation for operator 5, (F1, F2) Distance and angle deviation for operator 6.

analyzed according to CBCT data. The actual deviation from postoperative analysis is often greater than the deviation displayed by the dynamic navigation software during the operation for the following reasons.

First, there were errors in the CBCT process. Previous studies indicated that there was a deviation between CBCT reconstructed data and real data, and the magnitude of the deviation was related to the imaging range of CBCT.[34] The

Figure 3 (*continued*).

deviation of CBCT data impacts the positioning results. Second, there were errors in the calibration and registration process of the dynamic navigation technology, which were the systematic errors of the dynamic navigation technology itself, affecting the positioning deviation of the dynamic navigation technology.[12,22,35,36] Third, there were errors in the operation process. The trephine vibrates in the process of drilling into the models. The tracking device of the navigation system can track only the real-time position of the end of the handpiece. The continuous vibration of the top of the trephine makes the actual drilling position and angle different from those of the situation without vibration. Furthermore, the guidance of dynamic navigation lagged behind the operation. After the deviation exceeded the allowable range, the operator needed to capture the change information and stop the operation, while the direction and position deviation of the trephine were outside the tolerance before the operation was stopped. The common results of these three errors caused the actual drilling error to be larger than the positioning deviation value displayed by the navigation.

In conclusion, the goal of this study was to guide the promotion of dynamic navigation techniques in endodontic apical surgery. The learning difficulty and the learning curve of dynamic navigation in endodontic apical surgery were explored for the first time. The results suggested that operators without experience in dynamic navigation must practice to master dynamic navigation operations. For this navigation system, those without experience can master dynamic navigation operations after 7 exercises under the conditions of this study. Dynamic navigation technology still has some shortcomings, such as the need to wear special devices to take CBCT, the heavier weight of the handpiece with the tracker, and the complex operation process. In the future, dynamic navigation should be continuously improved, including lightweight and simplified upgrades to optimize the operating experience, and evaluation of the dynamic navigation in clinical applications should also be conducted.

Declaration of competing interest

The authors declare no conflicts of interest associated with this manuscript.

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