Influence of Depth and Choice of Operating Instruments on the Precision of Dynamic Navigation Systems

Xiao Xiang HUANG[1], Ding Xiang YUAN[1], Ben Xiang HOU[1]

Objective: *To evaluate the precision and efficiency of dynamic navigation-assisted trephines and fissure drills at varying depths utilising a 3D printed model.*

Methods: *A computer-designed in vitro standardised model was 3D printed using photosensitive resin, with hemispherical cavities reserved at depths of 5, 10 and 15 mm from the outer surface of the model. CBCT scans were taken before the procedure, and the data were imported into dynamic navigation software. Navigation paths were planned and executed using a trephine with a diameter of 4 mm and a fissure drill with a diameter of 1.2 mm guided by the dynamic navigation system. Ten procedures were performed at each depth. Postoperative CBCT scans were taken to reconstruct the navigated trajectories, and the platform deviations, end deviations and angular deviations were calculated by comparing the actual paths with the planned paths. The operating time was recorded.*

Results: *Under the guidance of the dynamic navigation system, the mean platform, end and angular deviations for trephines were 0.34 ± 0.17 mm, 0.25 ± 0.15 mm and 1.02 ± 0.49 degrees, respectively. For fissure drills, the mean deviations were 0.29 ± 0.13 mm, 0.31 ± 0.18 mm, and 1.33 ± 0.98 degrees, respectively. No significant differences were found with different depths or instrument types ($P > 0.05$). High-speed handpieces with fissure drills showed superior efficiency to low-speed handpieces with trephines ($P < 0.001$).*

Conclusion: *Dynamic navigation technology achieved good accuracy within a 15-mm depth range. The use of a trephine or fissure drill did not affect the accuracy of the dynamic navigation technique. High-speed handpieces with fissure drills showed superior efficiency.*

Keywords: *CBCT, computer-assisted, dynamic navigation, 3D printing*

Chin J Dent Res 2025;28(3):209–217; doi: 10.3290/j.cjdr.b6553449

The widespread adoption and application of dental microscopes have enabled dental practitioners to visualise the internal structures of pulp chambers and root canals since the 1990 s. This advancement has improved the precision and prognosis of endodontic treatment significantly; however, challenges arise in cases of severe root canal calcification, where there is difficulty locating periapical lesions, or where the operative area is in proximity to vital anatomical structures. All these pose risks during endodontic treatment, even for experienced endodontists. The emergence of static and dynamic guidance technologies has revolutionised the approach to treating complex and challenging endodontic cases. In contrast to static guide treatment, dynamic navigation technology encapsulates 3D medical imaging visualisation, image registration and spatial localisation within a single system. It eliminates the need for the extra step of guide printing, enabling real-time and dynamic precise targeting of the lesion area.[1]

In dental practice, chairside dynamic navigation–assisted procedures were initially applied in the field of oral implantology. It was not until 2019 that this technology was formally introduced in endodontics.[2] The past 5 years have seen a steady and notable increase in the number of studies focusing on dynamic navigation–assisted endodontic treatment. Currently, instruments

1 Center for Microscope Enhanced Dentistry, Beijing Stomatological Hospital, Capital Medical University, Beijing, P.R. China.

Corresponding author: Dr Ben Xiang HOU, Center for Microscope Enhanced Dentistry, Beijing Stomatological Hospital, Capital Medical University, No.22 Xin Rong Street, Daxing District, Beijing 100162, P.R. China. Tel: 86-10-58352000. Email: Endohou@163.com.

This study was supported by the Beijing Municipal Science & Technology Commission (no. Z191100006619037).

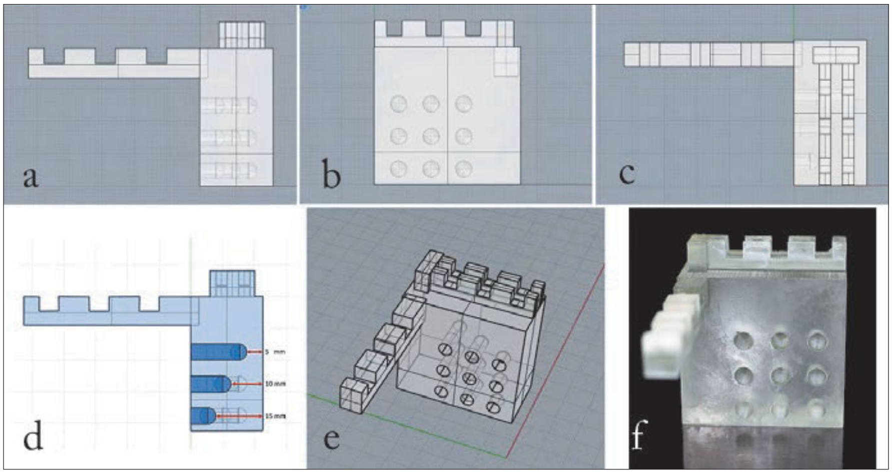

Fig 1 Computer-aided design and 3D printing of models: side view **(a)**, top view **(b)** and frontal view of the model **(c)**. Two-dimensional image of the model showed different lengths of the pathways **(d)**; 3D image of the model **(e)**; 3D printing model **(f)**.

for dynamic navigation in endodontic treatment are primarily adapted from oral implantology. There are various kinds of navigation software for endodontic treatment nowadays. Research areas include establishing pulp cavity access, dealing with calcified root canals, removing fibre posts, retrieving separated instruments and performing endodontic microsurgery.[3-11] The goal of dynamic navigation–assisted endodontic treatment is precise localisation, but in vitro studies have shown some instances of positioning errors during procedures.[6] Thus, elucidating the factors affecting the precision of dynamic navigation is essential for achieving accurate guidance.

Research has indicated that the precision of dynamic navigation is influenced by a multitude of factors, including equipment, instruments, procedural elements, practitioner experience and patient-specific variables.[12] The current literature on dynamic navigation technology in clinical oral procedures is predominantly comprised of case reports and in vitro studies utilising extracted teeth or model teeth. Nevertheless, the diversity in materials, including teeth and model specimens, leads to significant inconsistencies in the precision outcomes of various studies.[5-7,13] It is therefore imperative to consider the influence of in vitro study models on the accuracy of dynamic navigation technology.

Currently, the instruments used for dynamic navigation in endodontic treatment include high-speed fissure drills and low-speed trephines; however, there is a lack of research on whether the choice of different instruments affects navigation precision. A previous study suggested that significant deviations occur when the access depth exceeds 5 mm during freehand procedures.[14] Thus, dynamic navigation assistance is crucial for accurate positioning in deeper access procedures; however, there is limited research on whether access depth affects the precision of dynamic navigation.

This study aims to investigate the precision and efficiency of trephine and fissure drill positioning under the guidance of a dynamic navigation system in standardised models of varying depths and provide experimental evidence for the clinical application of the dynamic navigation system in endodontics.

Materials and methods

Computer-aided design and 3D printing of models

Rhino 7 software (Robert McNeel & Associates, Seattle, WA, USA) was used to design the models to evaluate the clinical operational accuracy of the endodontic dynamic navigation system. The models were designed with spherical cavities and divided into three groups based on drilling depth (Fig 1a to e). The spherical cavities with a diameter of 4.5 mm were set at 5, 10 and 15 mm (n = 10 each) from the outer surface of the model, serving as target locations for navigation with the trephine and fissure drill. On the other side of the spherical cavity was a 4.5-mm-wide channel perpendicular to the outer surface of the model to facilitate the removal of supporting material during the printing process. A cantilever (9 mm wide and 52.5 mm long on the side of the model) and a groove (5 mm wide above the model) with a serrate structure were designed to ensure the stability of the positioning plate and registration device. Model data were exported in stereolithographic (STL) format and uploaded to an AccuFab-C1 s 3D printer (SHINING 3D, Hangzhou, China). Models were printed using SG01 resin (SHINING 3D), ensuring that there was no supporting structure inside the reserved cavities (Fig 1f).

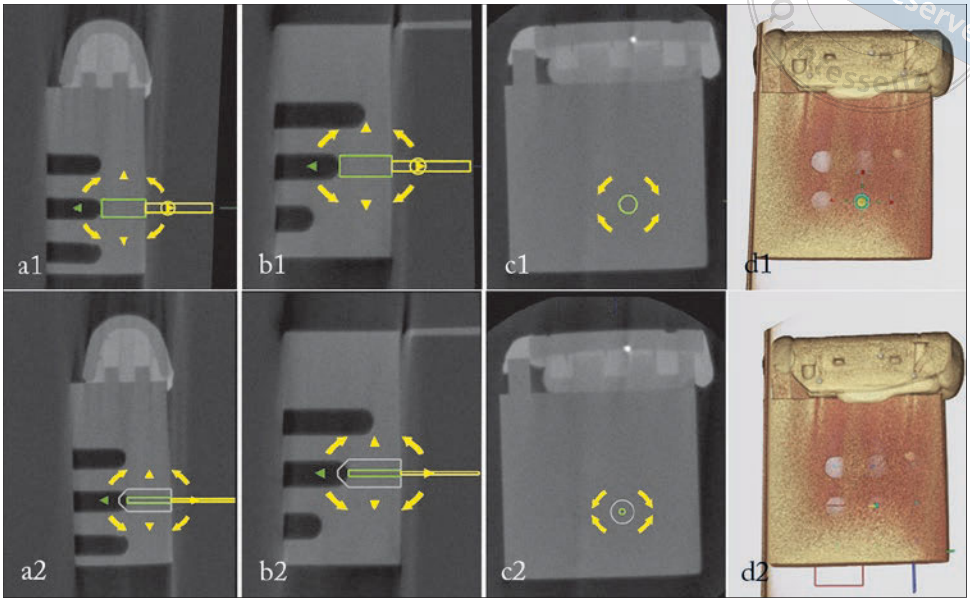

Fig 2a to d Preoperative plans of the trephine and fissure drill were made using CBCT images (trephine a1 to d1, fissure drill a2 to d2). Coronal plane **(a1 and a2)**; sagittal plane **(b1 and b2)**; axial plane **(c1 and c2)**; 3D image **(d1 and d2)**.

Model CBCT imaging and entry design

Impression material (HUGE Dental Material, Rizhao City, China) was placed in the registration device, which in turn was placed in the groove until the silicone rubber solidified completely. The CBCT data of the model were obtained with the same parameters (3D Dental Imaging System PP3, Planmeca, Helsinki, Finland; voxel size 0.2 mm; field of view 6 × 8 cm; voltage 90 kV; current 6.3 mA). The data obtained were saved in DICOM format and imported into an endodontic dynamic navigation software system (DRS-YTJX, 1.1, Yekebot Technology, Beijing, China).

In the trephine approach, a trephine with a diameter of 4 mm and working length of 15.1 mm (818-102 2#, Changsha Tiantian Dental Equipment, Changsha, China) was selected for the dynamic navigation software. The rotational speed was set to 1200 rpm and the torque to 35 Ncm for the approach design. The planned position of the trephine was adjusted in the axial, coronal and sagittal planes (Fig 2a1 to d1): (1) depth: the front end of the trephine was tangential to the front part of the hemisphere according to the software; (2) two-dimensional position: the central axis of the trephine passing through the midline of the posterior cavity channel; and (3) angle: the angle between the edge of the trephine and the edge line of the model was 90 degrees. By limiting the planned positions of the trephine in two-dimensional planes, the 3D position of the trephine in the software was determined to be tangential to the front of the hemispherical body at the planned depth, with the central axis of the trephine reaching the vertex of the hemisphere. The angle was perpendicular to the outer surface of the model and parallel to the midline of the cavity channel. This spatial position was set as the target position for guiding trephine entry in endodontic dynamic navigation.

In the fissure drill approach, a fissure drill with a diameter of 1.2 mm and a total length of 31 mm (H254LE, Gebr. Brasseler, Lemgo, Germany) was selected, and a turbine handpiece (NSK, Tokyo, Japan) was used for entry design. The planned position of the fissure drill was adjusted in the axial, coronal and sagittal planes (Fig 2a2 to d2): (1) depth: the front end of the drill tangential to the front of the hemispherical body according to the software; (2) two-dimensional position: the central axis of the drill passing through the midline of the posterior cavity channel; and (3) angle: the angle between the edge of the drill and the edge line of the model was set to 90 degrees. By limiting the planned positions of the fissure drill in two-dimensional planes, the 3D position of the fissure drill in the software was determined to be tangential to the front of the hemispherical body at the planned depth, with the central axis of the fissure drill reaching the vertex of the hemisphere. The angle was perpendicular to the outer surface of the model and parallel to the midline of the cavity channel. This spatial position was set as the target position for guiding fissure drill entry in endodontic dynamic navigation.

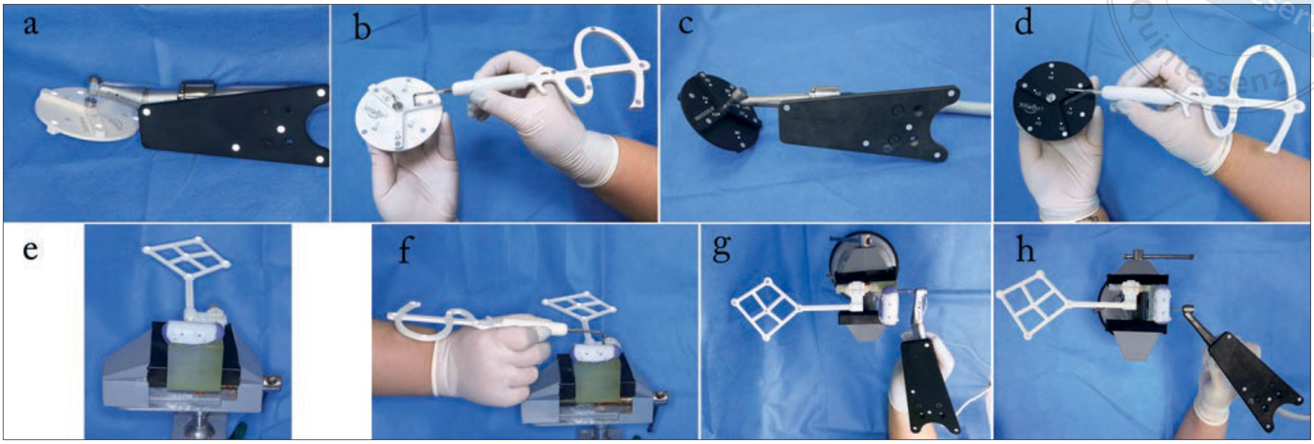

Fig 3a to h Establishment of trephine and fissure drill paths under dynamic navigation. Calibration **(a and b)**; trephine **(c and d)**; fissure drill **(a to d)**; registration **(e and f)**; visualisation of the drilling process in practice **(g and h)**.

Establishment of trephine and fissure drill paths under dynamic navigation

The planned path file was imported into the dynamic navigation system (DRS-YTJX, Yakebot Technology, Beijing, China). The calibration plate with positioning points was then assembled into a handpiece for drill tip calibration. After completing probe and disc calibration (Fig 3a to d), extraoral positioning markers were inserted into the positioning plate that was fixed on the model (Fig 3e). The calibration probe was placed on a positioning plate with six indicated markers for registration (Fig 3f). After registration, the extraoral positioning marker and headpiece end were identified by the system in real time. Subsequently, surgery was performed with the handpiece controlled by the operator under the dynamic navigation–guided system following a preoperatively planned path.

A trephine with a diameter of 4 mm was mounted on the low-speed handpiece, and a 1.2-mm fissure drill was mounted on the high-speed handpiece. An operator with more than 20 years of experience in dynamic navigation operations completed the trephine and fissure drill approach operations under the navigation system and recorded the operative time (Fig 3g and h).

The maximum allowable deviation was set to 0.3 mm and the maximum allowable deviation angle was 5 degrees. When the distance and angular deviation indicated by the dynamic navigation system were less than or equal to the allowable values, drilling was continued. When the distance was greater than the allowable value, drilling was stopped, and the position and angle of the handpiece were adjusted to achieve the needed distance and angle deviation (Fig 4a and b). As the drill continued to penetrate, the depth prompt bar of the navigation system displayed the current remaining depth and changed colour continuously. When the depth of the dynamic navigation system reached 0.0 mm, drilling was stopped. A total of 10 entries were completed for each of the hemispheres with depths of 5, 10 and 15 mm according to the above standards.

Model CBCT data reconstruction and analysis

Postoperative CBCT images of the model were taken under the same parameters used for preoperative imaging. Preoperative and postoperative CBCT data were imported into dynamic navigation accuracy analysis software (Dentalnavi 2.0, Yakebot Technology). Utilising the software's image fusion capabilities in conjunction with manual selection of shared reference points to automatically align preoperative and postoperative CBCT data. The deviation between the actual path and the planned path was calculated automatically, including platform deviation (A), end deviation (B) and angular deviation (C) (Fig 5). Platform deviation was the 3D deviation of the entry point between the planned and actual drilling paths; end deviation was the 3D deviation of the endpoint between the planned and actual drilling paths; and angular deviation was the angular deviation between the long axis of the planned drilling path and that of the actual drilling path.

Statistical analysis

The data were analysed using SPSS software (version 24.0; IBM, Armonk, NY, USA). The platform, end and angular deviation at different entry depths and for different operating instruments were analysed. Descriptive

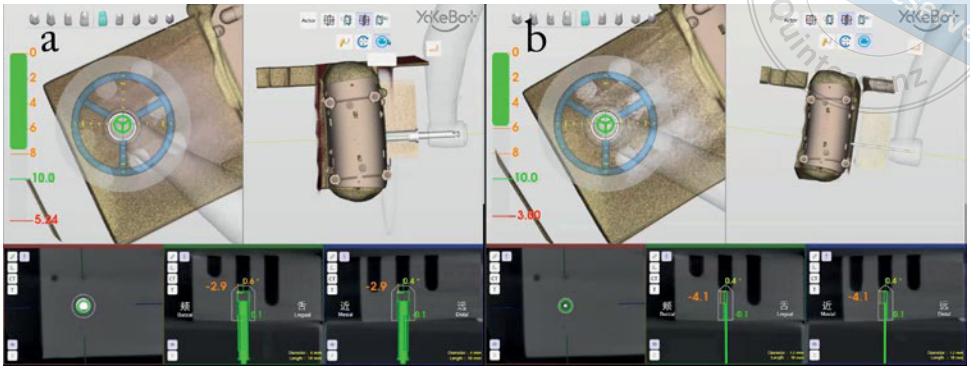

Fig 4a and b Visualisation of the drilling process under assistance of the dynamic navigation in the software. Trephine **(a)**; fissure drill **(b)**.

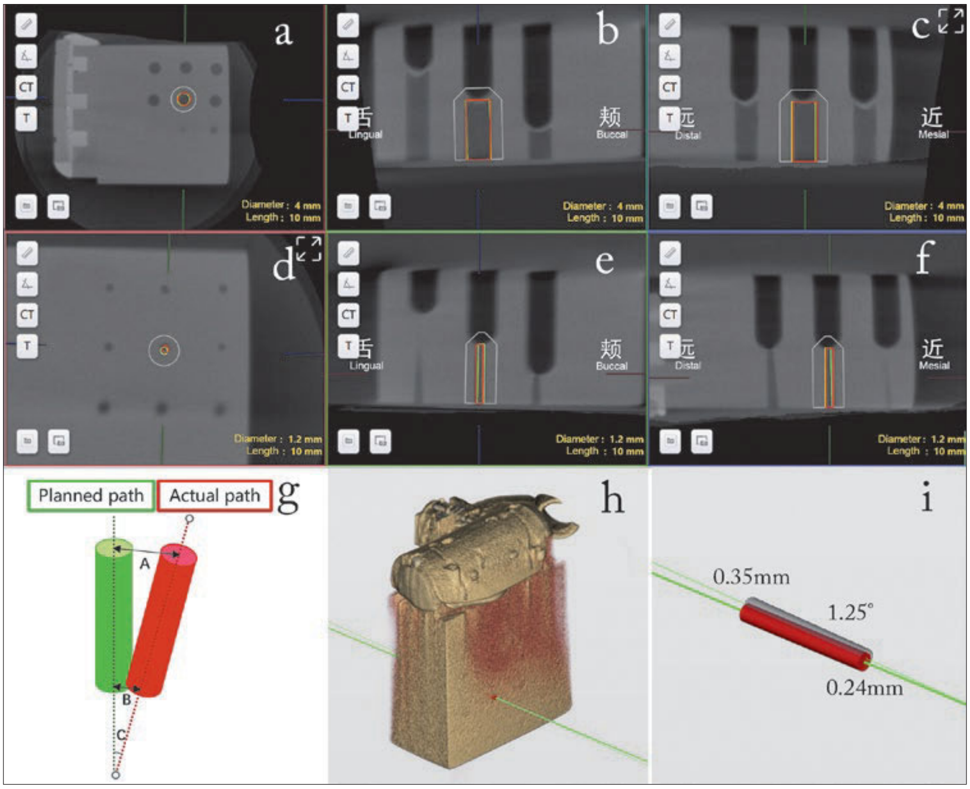

Fig 5a to i Schematic diagram of postoperative accuracy measurement and software analysis. Recognition of the planned path (green) and actual path (red) following superimposition of the preoperative and postoperative CBCT images: trephine **(a to c)**; fissure drill **(d to f)**; accuracy measurement schematic diagram (A, platform deviation; B, end deviation; C, angular deviation) **(g)**; schematic diagram of planned path and actual path on the 3D reconstruction model **(h)**; accuracy data automatically measured in the analysis software **(i)**.

statistics were expressed as mean ± standard deviation. A one-sample Kolmogorov-Smirnov test was used to check whether the samples were normally distributed.

One-way analysis of variance (ANOVA) was employed to check whether there were any statistical differences between groups when the same drill was inserted into different depths. An independent samples *t* test was used to compare whether there were statistical differences in platform, end and angular deviation for different drill types at identical depth. A Mann-Whitney U test was used to analyse differences in operation time between different operating instruments at the same depth. The level of significance was set at $P < 0.05$.

Results

Influence of depth on accuracy of dynamic navigation

Under the guidance of the dynamic navigation system, the mean platform, end and angular deviation of the trephine and fissure drill at depths of 5, 10 and 15 mm are shown in Tables 1 and 2.

When using the same drilling tool (trephine or fissure drills), there were no significant differences in platform, end and angular deviation among the 5-, 10- or 15-mm groups with the assistance of dynamic navigation ($P > 0.05$).

Table 1 Platform, end and angular deviation of dynamic navigation–guided trephines at different depths.

Deviation	Overall data	5 mm	10 mm	15 mm	F	*P* value
Platform deviation (mm)	0.34 ± 0.17	0.31 ± 0.24	0.35 ± 0.16	0.36 ± 0.08	0.321	0.728
End deviation (mm)	0.25 ± 0.15	0.27 ± 0.20	0.27 ± 0.15	0.22 ± 0.08	0.381	0.687
Angular deviation (°)	1.02 ± 0.49	1.17 ± 0.74	0.93 ± 0.29	0.97 ± 0.34	0.662	0.524

Table 2 Platform, end and angular deviation of dynamic navigation–guided fissure drills at different depths.

Deviation	Overall data	5 mm	10 mm	15 mm	F	*P* value
Platform deviation (mm)	0.29 ± 0.13	0.25 ± 0.10	0.35 ± 0.10	0.28 ± 0.17	1.618	0.217
End deviation (mm)	0.31 ± 0.18	0.25 ± 0.12	0.38 ± 0.25	0.31 ± 0.13	1.557	0.229
Angular deviation (°)	1.33 ± 0.98	1.54 ± 1.41	1.44 ± 0.45	1.01 ± 0.63	0.806	0.457

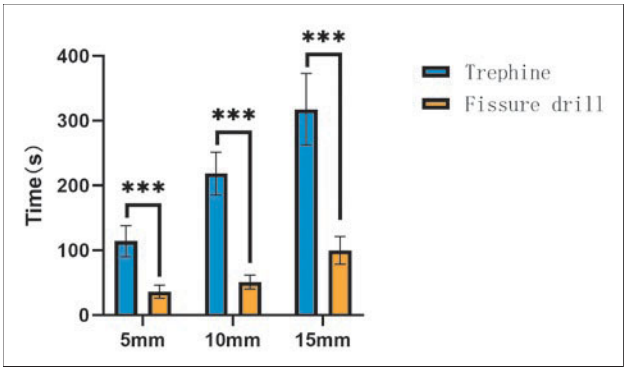

Fig 6 Surgical times for the trephine and fissure drill at different depths.

Influence of operating instruments on accuracy of dynamic navigation

At the same depth, when comparing the use of a low-speed handpiece with a trephine and a high-speed handpiece with a fissure drill under the assistance of dynamic navigation, there were no statistically significant differences in platform, end or angular deviation ($P > 0.05$).

Influence of operating instruments on efficiency of operation under the guidance of dynamic navigation

When evaluating operational efficiency, under the guidance of dynamic navigation, the high-speed handpiece equipped with a fissure drill demonstrated notably higher effectiveness compared to the low-speed handpiece equipped with a trephine at equivalent depths ($P < 0.001$) (Fig 6).

Discussion

Dynamic navigation harmonises the 3D visualisation of medical imaging with registration and spatial localisation technologies, streamlined through an integrated system of software, computers and optical positioning instruments.[1] It dynamically guides the direction, angle and depth of operation in real time. Research on its accuracy is mostly based on in vitro studies using extracted teeth or model teeth; however, there is significant variation in the research results due to the different experimental models used in various studies. For instance, in the context of dynamic navigation–assisted calcified root canal clearance, Torres et al[6] and Jain et al[7] used different 3D printed models, resulting in significant differences in platform, end and angular deviation. Similarly, in studies involving the establishment of pulp chamber access assisted by dynamic navigation, there were substantial differences in the results between models of single-root anterior teeth and those of multi-root posterior teeth.[5,13] Currently, there is still a lack of systematic research on the accuracy of dynamic navigation technology itself. Thus, the present study builds upon previous research models[15] by improving and designing standard model blocks to validate the accuracy of dynamic navigation. Dynamic navigation utilises an optical system to track headpieces and fixed markers inside the patient's mouth, calculating the relative position between the patient and surgical instruments. The system updates coordinates and positions in real time within the software image coordinate system, guiding the positioning of surgical instruments. Hence, preoperative calibration and registration are crucial. Studies indicate that different calibration and registration devices or methods can affect the accuracy of dynamic navigation to some extent.[16,17] Instances of navigation failure, attributable to the misplacement of registration devices or the omission of re-registration following adjustments to the procedural pathway, have been documented.[18] To eliminate the impact of loose registration devices on navigation accuracy, the model in the present study was designed with double-row concave grooves and the cantilever was also designed with a groove, facilitating the fixation of the reference plate. To eliminate the impact of different distances to the registration device on accuracy, this model was designed with channels of different depths to the registration device at the same distance. Clinically, the periradicular lesion area often presented as a spherical shape surrounding the root apex. The model in the present study simulated this periradicular lesion area with a spherical cavity. A channel was necessary during the resin printing process to facilitate the removal of supporting material; thus, the rear part was also designed as an empty duct. During endodontic microsurgery, the lesion area was directly probed after osteotomy. In the present study, however, to facilitate the observation of the endpoint of the procedure, it was set as tangential to the front of the hemispherical body, without being perforated to the subsequent channel. Therefore, after surgery, especially with the trephine, some resin material might remain at the centre. The present authors set the endpoint of the actual path as the plane formed by the circular section created by the trephine, which did not affect the accuracy analysis postoperatively.

The accuracy of dynamic navigation may be influenced by operator experience, including clinical experience and experience using navigation instruments. Previous studies indicated that there was no significant difference in accuracy between novice and experienced endodontists when using dynamic navigation.[3,19] Thus, an experienced clinical operator does not directly improve the accuracy of dynamic navigation, but the operator's experience using navigation instruments affects it. In another investigation focusing on navigation-assisted dental implant surgery, a comparative analysis was conducted on the precision of the initial 50 implants versus the final 50 implants within a series of 231 implants placed by surgeons utilising navigational aids.[20] The study revealed that the precision of the last 50 implants was considerably higher than that of the first 50.[20] Several studies have shown that dynamic navigation technology requires practice, and the operating experience of the instrument affects the accuracy of dynamic navigation.[21-23] Therefore, in the present study, surgery was performed by a skilled user who had employed dynamic navigation more than 20 times under the guidance of the dynamic navigation system, eliminating the influence of operator experience on the accuracy of dynamic navigation.[24]

The surgical approach for apical surgery differs from that for implantation. To simulate the surgical pathway of apical surgery, the direction of drill insertion in the present study was designed to be horizontal. The distances from the roots to the buccal bone plates are variable. In clinical practice, the maxillary molar palatal roots and the mandibular molar lingual roots, which are more challenging to operate on, are approximately 10 to 12 mm and 6 to 8 mm away from the buccal bone plate, respectively.[25-28] The paths designed in this experiment ranged from 5 to 15 mm, which meet the drilling depth requirements of most endodontic microsurgeries in the posterior tooth area from the buccal approach. In this study, with increasing depth, there was no significant deviation in the platform, end or angular deviations of the drills under dynamic navigation assistance. Consistent findings were reported in the study conducted by Dianat et al[14] on dynamic navigation–assisted osteotomies and root-end resections in cadaveric jaws, where no significant variance in procedural accuracy was detected between depths exceeding 5 mm and those falling short of 5 mm. However, another study has shown that with increasing depth, there is a significant increase in platform deviation and end deviation in dynamic navigation–aided drilling.[15] The present authors suspect that this difference may be related to the use of different navigation software.

A trephine with an outer diameter of 4 mm was used in the present study, primarily based on the suggestion from Kim and Kratchman[29] that the ideal diameter of an osteotomy be approximately 4 mm, leaving enough space to manipulate the ultrasonic tip and other instruments within its confines. On the other hand, a fissure drill with a diameter of 1.2 mm was chosen because this tool is commonly used for osteotomy in freehand endodontic microsurgery and non-surgical treatment under dynamic navigation assistance. The present results showed that the platform deviation of the trephine was greater than that of the fissure drill. Though not statistically significant, there was a noticeable tendency for the trephine to exhibit shaking during procedures, particularly when the operator attempted to manipulate it with one hand while simultaneously monitoring the navigation screen, resulting in potential instability. The extent of this shaking can impact the precision of the positioning. Chen et al[30] also mentioned the same issue in their study and suggested that stability could be improved by holding the trephine with two hands. Stability increases when the trephine penetrates 1 to 2 mm into the bone surface; however, further research is needed on how to increase the stability of trephine operations under dynamic navigation assistance.

The results showed that at the same depth, there was no significant difference in accuracy between dynamic navigation–aided trephines and fissure drills. Within the depth range of 15 mm, both trephines and fissure drills were able to maintain a high level of accuracy. When using a fissure drill in dynamic navigation–assisted endodontic microsurgery for osteotomy, since the fissure drill has a diameter of 1.2 mm, it is necessary to expand the area to obtain an adequate operating field. However, the dynamic navigation system may sound an alarm as the drilling range exceeds the allowable error value, because the dynamic navigation system is designed for central point positioning. Thus, using dynamic navigation to guide high-speed fissure drills for osteotomy may lead to problems such as reaching the target depth but having insufficient range and limited visibility for subsequent processes. Currently, fissure drills are more suitable for nonsurgical endodontic treatment with dynamic navigation assistance. For dynamic navigation–aided surgical treatment, a trephine is more appropriate. A trephine with a diameter of 4 mm was used for osteotomy, and the bone window diameter was 4 mm after drilling, providing the premise for subsequent root-end resection, cavity preparation and filling. The trephine could also complete osteotomy and root-end resection simultaneously, simplifying the surgical steps; however, due to the shape of the trephine drill, the cross-section of the apical resection was curved. A study showed that the bevel of curved edges may lead to stress concentration, which may affect the prognosis.[31] Thus, the curved edge should be removed using a high-speed handpiece with a diamond or an ET18D ultrasonic tip in this kind of situation.

The duration of the surgical procedure is a critical factor that can influence the prognosis of endodontic microsurgery for patients. Shortening the surgical time could reduce fatigue for the operator and the patient, decrease the probability of surgical visual impairment due to bleeding, and further impact the possibility of surgical success.[14] A study also indicated that shorter surgical times could alleviate postoperative pain.[32] In the present study, the surgical time of the trephine group was significantly longer than that of the fissure drill group. In addition to the high rotation speed of the high-speed handpiece, the extended surgical time with a trephine was attributed to the initial instability caused by its shaking and slipping during positioning, as well as the potential for interruptions when cylindrical debris was ground down by the drilling process and became lodged within the trephine's cavity at a certain depth. Furthermore, the efficacy of a trephine diminishes over time as the front cutting edge becomes increasingly worn with each use. The cutting efficiency of a worn trephine is significantly diminished, consequently impacting the duration of the surgical procedure.

Conclusion

In summary, dynamic navigation technology achieved good accuracy within a range of 15 mm. The use of trephines or fissure drills did not affect the accuracy of the dynamic navigation technique. The results of this study provide a basis for ensuring the safety of in vivo experiments.

Acknowledgements

The authors wish to thank Yong Qi Wang and Qian Wu from the Center for Microscope Enhanced Dentistry, Beijing Stomatological Hospital, Capital Medical University, Beijing, China for their assistance with CBCT scanning and the related technical support. The authors also wish to thank Ying Wang from Yakebot Technology, Beijing, China, for dynamic navigation technical support.

Conflicts of interest

The authors declare no conflicts of interest related to this study.

Author contribution

Dr Xiao Xiang HUANG made the model work, collected the data and drafted the manuscript; Ding Xiang YUAN contributed to the data analysis and manuscript revision; Dr Ben Xiang HOU designed and supervised the study.

(Received Oct 09, 2024; accepted Mar 06, 2025)

References

1. Bobek SL. Applications of navigation for orthognathic surgery. Oral Maxillofac Surg Clin North Am 2014;26:587–598.
2. Gambarini G, Galli M, Stefanelli LV, et al. Endodontic microsurgery using dynamic navigation system: A case report. J Endod 2019;45:1397–1402.e6.
3. Connert T, Leontiev W, Dagassan-Berndt D, et al. Real-time guided endodontics with a miniaturized dynamic navigation system versus conventional freehand endodontic access cavity preparation: Substance loss and procedure time. J Endod 2021;47:1651–1656.
4. Gambarini G, Galli M, Morese A, et al. Precision of dynamic navigation to perform endodontic ultraconservative access cavities: A preliminary in vitro analysis. J Endod 2020;46:1286–1290.
5. Jain SD, Saunders MW, Carrico CK, Jadhav A, Deeb JG, Myers GL. Dynamically navigated versus freehand access cavity preparation: A comparative study on substance loss using simulated calcified canals. J Endod 2020;46:1745–1751.
6. Torres A, Boelen GJ, Lambrechts P, Pedano MS, Jacobs R. Dynamic navigation: A laboratory study on the accuracy and potential use of guided root canal treatment. Int Endod J 2021;54:1659–1667.
7. Jain SD, Carrico CK, Bermanis I. 3-dimensional accuracy of dynamic navigation technology in locating calcified canals. J Endod 2020;46:839–845.
8. Dianat O, Nosrat A, Tordik PA, et al. Accuracy and efficiency of a dynamic navigation system for locating calcified canals. J Endod 2020;46:1719–1725.
9. Janabi A, Tordik PA, Griffin IL, et al. Accuracy and efficiency of 3-dimensional dynamic navigation system for removal of fiber post from root canal-treated teeth. J Endod 2021;47:1453–1460.
10. Karim MH, Faraj BM. Comparative evaluation of a dynamic navigation system versus a three-dimensional microscope in retrieving separated endodontic files: An in vitro study. J Endod 2023;49:1191–1198.
11. Aldahmash SA, Price JB, Mostoufi B, et al. Real-time 3-dimensional dynamic navigation system in endodontic microsurgery: A cadaver study. J Endod 2022;48:922–929.
12. Jorba-García A, González-Barnadas A, Camps-Font O, Figueiredo R, Valmaseda-Castellón E. Accuracy assessment of dynamic computer-aided implant placement: A systematic review and meta-analysis. Clin Oral Investig 2021;25:2479–2494.
13. Zubizarreta-Macho Á, Muñoz AP, Deglow ER, Agustín-Panadero R, Álvarez JM. Accuracy of computer-aided dynamic navigation compared to computer-aided static procedure for endodontic access cavities: An in vitro study. J Clin Med. 2020;9:129.
14. Dianat O, Nosrat A, Mostoufi B, Price JB, Gupta S, Martinho FC. Accuracy and efficiency of guided root-end resection using a dynamic navigation system: A human cadaver study. Int Endod J 2021;54:793–801.
15. Liu SM, Zhao YJ, Wang XY, Wang ZH. In vitro evaluation of positioning accuracy of trephine bur at different depths by dynamic navigation [in Chinese]. Beijing Da Xue Xue Bao Yi Xue Ban 2022;54:146–152.
16. Wang Z, Chen C, Qin L, Li F, Chen Y, Meng L. Accuracy and efficiency of endodontic microsurgery assisted by dynamic navigation based on two different registration methods: An in vitro study. J Endod 2023;49:1199–1206.
17. Pei X, Weng J, Sun F, Ma Y, Iao S, Liu X. Accuracy and efficiency of a calibration approach in dynamic navigation for implant placement: An in vitro study. J Dent Sci 2024;19:51–57.
18. Yang X, Zhang Y, Chen X, Huang L, Qiu X. Limitations and management of dynamic navigation system for locating calcified canals failure. J Endod 2024;50:96–105.
19. Chen C, Wang FS, Zhang R, Bian Z, Meng LY. An in vitro model study of computer-guided endodontic microsurgery [in Chinese]. Zhonghua Kou Qiang Yi Xue Za Zhi 2022;57:44–51.
20. Stefanelli LV, DeGroot BS, Lipton DI, Mandelaris GA. Accuracy of a dynamic dental implant navigation system in a private practice. Int J Oral Maxillofac Implants 2019;34:205–213.
21. Marques-Guasch J, Rodriguez-Bauzá R, Satorres-Nieto M, Hom-Lay W, Hernández-Alfaro F, Gargallo-Albiol J. Accuracy of dynamic implant navigation surgery performed by a novice operator. Int J Comput Dent 2022;25:377–385.
22. Sun TM, Lan TH, Pan CY, Lee HE. Dental implant navigation system guide the surgery future. Kaohsiung J Med Sci 2018;34:56–64.
23. Block MS, Emery RW, Lank K, Ryan J. Implant placement accuracy using dynamic navigation. Int J Oral Maxillofac Implants 2017;32:92–99.
24. Golob Deeb J, Bencharit S, Carrico CK, et al. Exploring training dental implant placement using computer-guided implant navigation system for predoctoral students: A pilot study. Eur J Dent Educ 2019;23:415–423.
25. Huang X, Xu J, Hou B, Wang Y. Proximity of maxillary molar palatal roots to adjacent structures for endodontic microsurgery: A cone-beam computed tomography study. BMC Oral Health 2025;25:21.
26. Kang SH, Kim BS, Kim Y. Proximity of posterior teeth to the maxillary sinus and buccal bone thickness: A biometric assessment using cone-beam computed tomography. J Endod 2015;41:1839–1846.
27. Porto OCL, Silva BSF, Silva JA, et al. CBCT assessment of bone thickness in maxillary and mandibular teeth: An anatomic study. J Appl Oral Sci 2020;28:e20190148.
28. Jeon KJ, Lee C, Choi YJ, Han SS. Anatomical analysis of mandibular posterior teeth for endodontic microsurgery: A cone-beam computed tomographic evaluation. Clin Oral Investig 2021;25:2391–2397.
29. Kim S, Kratchman S. Modern endodontic surgery concepts and practice: A review. J Endod 2006;32:601–623.
30. Chen C, Zhang R, Zhang W, et al. Analysis of the accuracy of a dynamic navigation system in endodontic microsurgery: A prospective case series study. J Dent 2023;134:104534.
31. Yoo YJ, Perinpanayagam H, Kim M, et al. Stress distribution on trephine-resected root-end in targeted endodontic microsurgery: A finite element analysis. J Endod 2022;48:1517–1525.e1.
32. Hu W, Jiang WT, Hu N, Gu S. Effect of the duration of microscopic apical surgery on postoperative pain [in Chinese]. Shi Yong Lin Chuang Yi Yao Za Zhi 2022;26:16–19.