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University of Maryland Dental School Endodontic Residency Fall 2017- 2020
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Professional Experience

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Shahid Beheshti University of Medical Sciences, Tehran-Iran

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Manuscript publication in the past 5 years

"Effect of vibratory stimulation on pain during local anesthesia injection: a clinical trial." Ghorbanzadeh S, Alimadadi H, Zargar N, Dianat O. Restor Dent Endod 2019; 44:e40.

"The Effect of Calcium Hydroxide and Nano-calcium Hydroxide on Microhardness and Superficial Chemical Structure of Root Canal Dentin: An Ex Vivo Study." Naseri M, Eftekhar L, Gholami F, Atai M, Dianat O. J Endod. 2019; 45:1148-54.

"The efficacy of supplemental intraseptal and buccal infiltration anesthesia in mandibular molars of patients with symptomatic irreversible pulpitis." Dianat O, Mozayeni MA, Layeghnejad MK, Shojaeian S. Clin Oral Investig. 2020; 24:1281-86.

"Effect of Root Canal Preparation Techniques on Crack Formation in Root Dentin." Shantiaee Y, Dianat O, Mosayebi G, Namdari M, Tordik P. J Endod. 2019; 45:447-52.

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"Efficacy of preoperative ibuprofen and meloxicam on the success rate of inferior alveolar nerve block for teeth with irreversible pulpitis." Shantiaee Y, Javaheri S, Movahhedian A, Eslami S, Dianat O. Int Dent J. 2017; 67:85-9.

"Endodontic repair in immature dogs' teeth with apical periodontitis: blood clot vs plasma rich in growth factors scaffold." Dianat O, Mashhadi Abas F, Paymanpour P, Eghbal MJ, Haddadpour S, Bahrololumi N. Dent Traumatol. 2017; 33:84-9.

"Outcomes of revascularization treatment in immature dog's teeth". Khademi AA, Dianat O, Mahjour F, Razavi SM, Younessian F. Dent Traumatol. 2014; 30:374-9.

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Abstract

Title of Dissertation: The Accuracy and Efficiency of a Dynamic 3D Navigation System for Negotiating Calcified Canals

Seyed Omid Dianat, Master of Science 2020

Dissertation directed by: Priya Chand, DDS, MS, Endodontic Division, School of Dentistry

The purpose of this study is to compare the use of a dynamic navigation system (DNS) to a freehand (FH) method for locating calcified canals. Sixty single-rooted teeth with obliterations were selected. In the DNS group, access preparation was made under navigation and in the FH group without any guidance. Linear and angular deviations and reduced dentin thickness were measured. Furthermore, efficiency was evaluated. The mean linear and angular measurements showed significantly less deviations in the DNS group compared to the FH group. Reduced dentin thickness, at both levels, was significantly less in the DNS group. Furthermore, DNS was faster and more successful than FH method. The DNS group showed only one unsuccessful attempt, compared to five perforations and three large transportations in the FH group. Within the limitation of this study, the dynamic navigation system allowed for more accurate and efficient negotiation of the calcified root canal system.

The Accuracy and Efficiency of a Dynamic 3D Navigation System for Negotiating Calcified Canals

by

Seyed Omid Dianat

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, Baltimore in partial fulfillment
of the requirements for the degree of
Master of Science
2020

Acknowledgements

My sincere gratitude for the help and support from the following individuals whose contribution made this study possible:

Dr. Patricia Tordik, my primary mentor, for her groundwork and guidance through grant proposal submission to the Foundation of Endodontics.

Dr. Behzad Mostoufi for his fantastic help in operator calibration and training of the use of the X-guide system

Dr. Elaine Romberg, adviser and statistician, for her valuable analysis and revisions that aided in completion of this project

Dr. Priya Chand for her fruitful help in finalizing the thesis manuscript and presentation.

Dr. Jeffery Price for his support for taking the cone beam scans and calibrating us for CBCT measurements

Dr. Ali Nosrat for his great help as the second operator in both experimental groups

Dr. Sarah Aldamash for assisting me during the entire stage of this research, including execution, measurement and data collection.

This study was supported by an American Association of Endodontics Foundation grant

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List of Abbreviations

3 dimensional (3D)

Ali Nosrat (AN)

Analysis of variance (ANOVA)

Buccolingual (BL)

Buccopalatal (BP)

Cementoenamel junction (CEJ)

Computer-aided design/ computer-aided manufacturing (CAD/CAM)

Computer-assisted surgical (CAS)

Cone-beam computed tomography (CBCT)

Confidence interval (CI)

Computed tomography (CT)

Dental Operating Microscope (DOM)

Dynamic Navigation System (DNS)

Dynamic navigation (DN)

Elaine Romberg (ER)

Freehand (FH)

Manual technique (MN)

Mesiodistal (MD)

Omid Dianat (OD)

Pulp canal obliteration (PCO)

Reduced dentin thickness (RDT)

Standard deviation (SD)

Introduction

Calcified canals present a significant challenge to clinicians during root canal therapy. Healthy, diseased, and even unerupted teeth have pulpal calcifications. Calcification is a process involving the reduction in size of the intra-dental cavities as a result of hard-tissue formation by the cells of the vital pulp (1). It may end in complete calcification as a result of constant dentinogenesis. Their prevalence varies widely. The etiological factors for the formation of pulpal calcifications are not well understood; trauma, aging, various systemic diseases such as cardiovascular diseases could be causes of calcifications (2). Long-term irritation such as deep caries and restorations with proximity to the pulp have been proposed as possible implicated factors in the development of pulpal calcifications. Pulp canal obliteration (PCO) is mostly associated with dental trauma and occurs in 15 to 40% of patients after luxation injuries (1-3). It may also occur as a pulpal response to caries and restorations (4, 5) and after vital pulp therapy procedures (6). Furthermore, in the elderly patient, severe progressive calcification of root canal space can be observed due to apposition of secondary and tertiary dentin over time (7, 8). As Dr. John Ingle stated, endodontic access in the elderly becomes less about locating the pulp chamber and more about locating canal orifices (9). Additionally, calcification of root canal systems may arise as an adverse effect of orthodontic forces due to interference with pulpal blood supply (10, 11). Root canal treatment is not indicated in these cases unless clinical or radiographic signs of pulp necrosis are evident (12). However, 7 to 27% of teeth with PCO may develop apical periodontitis in the long term (2, 13, 14).

Histologic specimens of teeth with PCO usually present a persisting narrow root canal (15) but determining the correct location of the root canal is difficult (16). Root canal treatment is very challenging in these cases and is associated with a high failure rate.

Therefore, the American Association of Endodontists categorized the treatment of teeth with PCO as a high difficulty level (17). With an increased risk of perforation, much care must be exercised during access cavity preparation, canal negotiation and instrumentation. To avoid procedural mishaps, accurate preoperative radiographs from different angles are essential. In addition, knowledge and understanding of the anatomy and color differences of the pulp chamber floor can assist clinicians in identification of canal orifices (18).

Technology and calcified canals

Technological advances in locating calcified canals remain minimal. Some common aids in locating calcified canals include staining the chamber floor with 1% methylene blue dye, presence of canal bleeding points, and performing the sodium hypochlorite “champagne bubble” test (19). This was further improved by the introduction of surgical operating microscopes in early 1990s significantly enhanced canal localization. The use of magnification and illumination provided by the dental operating microscope and the use of ultrasonic tips and long-shank drills can aid in identification and instrumentation of calcified canals (20, 21).

3D imaging and calcified canals

CBCT provides 3-dimensional (3D) scans of the dentition and maxillofacial structure. CBCT was introduced in the late 1990s specifically to generate a reconstructed 3D image of the maxillofacial skeleton. One of the applications of CBCT is identification of narrow root canals (22, 23). Preoperative and intraoperative use of CBCT in complicated endodontic cases can help the practitioner in ensuring a safer procedure and ultimately a more predictable treatment outcome (24, 25). With voxel sizes measured in the tenths and hundredths of millimeters, CBCT allows 3D visualization to a level of accuracy that was not previously achievable.

Challenges encountered with DOM and CBCT

Even with the dental operating microscope and application of CBCT imaging, preparation of a proper and adequate access cavity may result in excessive loss of dentin structure. This impairs stability and thereby reduces the long-term prognosis of the tooth (26). Also, it is very time-consuming. Therefore, attempts continue to find a safer and more efficient method for canal negotiation.

Newer technology for managing of calcified cases

A significant advancement in endodontics was the introduction of a new treatment technique termed ‘guided endodontics’ which centered around computer aided system. This technique uses a printed template with incorporated sleeves that guides the bur to the root canal system resulting in an accurate access cavity preparation (27-30). This technique is currently being used for treatment of calcified anterior teeth (27, 30). Some of the technique’s limitations include additional treatment time, necessity of an intra-oral scan acquisition, template fabrication, inability to be used in posterior teeth, lack of real-time visualization and a pre-determined drill position that cannot be changed during the procedure.

Consistent with the 3D computer aided system, implant dentistry has adopted the ‘dynamic navigation’ approach. It is a passive optical system that allows the surgeon to visualize the implant preparation during the osteotomy drilling sequence. The position and angulation of the drill can be adjusted at any time during the surgery (30). This technique has the potential to be applied in endodontics for access cavity preparation especially in cases with severe canal calcification. In addition, it can be utilized in cases with dental developmental malformations such as dense invaginatus/evaginatus, for fiber post removal, even for performing a conservative osteotomy and root end resection in endodontic microsurgery.

Computer-assisted surgical (CAS) system

CBCT imaging has been an enabling technology in the development of computer-assisted surgical (CAS) implant placement systems. CAS systems include static or dynamic methods. The static CAS system uses a template fabricated with computer-aided design/computer-aided manufacturing (CAD/CAM) or 3D printing based on scans of the patient. Static surgical guides can be tooth-, mucosa-, or bone-supported. A drawback of static surgical guides is that once fabricated, the planned angulation, size, or type of implant cannot be easily changed. On the other hand, the dynamic CAS system is based on computer-aided surgical navigation technology and analogous to global positioning systems or satellite navigation. It has been used and investigated in several areas in medicine, such as neurosurgery and craniomaxillofacial surgeries (31,32). In this system, the position of the virtual implant is planned using the computer software and the imported preoperative CBCT data. Then a system of motion-tracking cameras tracks the patient, surgical handpiece and drill to present real-time positional and guidance feedback on a computer display. Understanding of indications and limitations of both types of CAS systems is important. While both systems are highly accurate based on previous studies, the dynamic navigation system provides the following advantages in implant surgical placement: 1) accurate and predictable outcome, 2) facilitated and faster workflow (the patient can be scanned, planned, and undergo surgery on the same day), 3) possibility of altering the plan during surgery based on the clinical situation, 4) real-time visualization of the entire field, and 5) the possibility of accuracy verification at all times.

Dynamic Navigation in Implant Dentistry

The Dynamic navigation system is a promising technology developed to guide the placement of dental implants in real time by a computer and based on information generated from the patient's computed tomography (CT) or CBCT scan (33-35). Several navigation tracking systems have been designed for this purpose. These systems are empowered by a motion tracking technology that tracks the positions of both the patient and the dental handpiece or drill throughout the dental procedure. The ideal implant position is planned digitally by the surgeon using CBCT scans before the surgery. Sensors or tracking markers attached to both the surgical handpiece and patient head or teeth transfer 3D spatial information to a camera or stereo-tracker. There are several companies that produce and market the systems. Table 1 shows a summary of current available systems on the market.

Table 1. Available dynamic navigation systems on the market for use in implant placement.

Device Name	**Company**	**Country of origin**	**FDA approval**	**Canada/ CE**
X-guide *	X-Nav Tech.	USA	Yes	Yes
Navident	ClaroNav	Canada	Pending	Yes
DenX Image	Image Navigation	Israel	Yes	Yes
Inliant	Inliant Dental Tech.	Canada	Pending	Yes

* The system used in this research

Advantages of Dynamic Navigation Systems

1) Virtually planning the surgery or other potential dental procedures beforehand permits for a well-prepared procedure
2) These systems decrease the likelihood of human error, since even the most experienced dentists, surgeons or endodontists can become distracted or lose the proper dimensional positioning of the drill.
3) Possibility of modification of the virtual plan during the procedure
4) Reduced patient chair time
5) Increased dentist efficiency
6) Predictable and reproducible outcome

Disadvantages of Dynamic Navigation Systems

1) High cost for the purchase of machine, updates, and maintenance of the system
2) Multiple need for recalibration during a single procedure
3) Inability of clinician to work through the dental operating microscope- Need for looking at the display while doing the guided procedure
4) Cumbersome and bulky sensors on both handpiece and patient
5) Additional cost of treatment for the patients
6) Need for a larger field of view Cone beam CT scans

Accuracy of dynamic navigation systems in implant placement

A couple of studies have evaluated the accuracy of these systems in implant placement. Studies by Emery *et al.* (34) and Block *et al.* (35,36) have evaluated X-guide systems that will be discussed later in this chapter. Kaewsiri *et al.* have done a randomized controlled trial evaluating the accuracy of static vs. dynamic computer-assisted implant surgery in single tooth space. A total of 60 patients in need of a single implant were randomly assigned to two groups of static and dynamic and implants were placed by one surgeon. Preoperative and postoperative CBCTs were overlaid and deviation analysis with the planned position was done. Results showed that the mean deviation at implant platform and implant apex in the static group was 0.97±0.44 mm and 1.28±0.46 mm, while in dynamic group was 1.05±0.44 mm and 1.29±0.50 mm, respectively. In addition, the angular deviation in static and dynamic group was 2.84±1.71 degrees and 3.06±1.37 degrees. The difference between two groups never reached a statistical significance. They concluded that both methods appear to have similar accuracy (37). The authors in this study haven't mention the brand and system specifications used for dynamic navigation implant placement.

Another group (Guzman *et al.*) has recently done an in-vitro study looking at the accuracy of static and dynamic computer-aided systems for implant placement. A total of 40 dental implants were placed randomly with either static or dynamic systems and deviations were calculated comparing the postoperative CBCTs with planned preoperative CBCT scans. No statistically significant differences were found between two groups at the coronal and apical levels in regard to linear deviation. However, the angular deflection in dynamic group was statistically higher than static experimental group (38).

X-guide Dynamic 3D Navigation (X-Nav Technologies, Lansdale, PA, USA)

The main parts of this system are:

1) A handpiece attachment
2) A patient jaw attachment (X-clip)
3) A system cart consisting of stereo cameras (tracker), a computer and monitor with robust X-guide software

This system is compatible with most CBCT 3D systems. A CBCT scan should be made with the X-clip fiducial in place, then the dentist will be able to import the scan into the software and plan the implant placement through its software. During the procedure, it is necessary to attach the sensor attachment to the handpiece and the jaw attachment to the patient X-clip. The X-guide has a patent-pending X-point technology that provides easy, color tracking of drill depth during surgery.

Accuracy of X-guide system in implant placement

The concept of utilizing some form of guidance system has been an area of interest in implant surgery. Older dynamic navigation systems were based on optical triangulation to track components using up to a dozen tracking points. However, the new system (X-guide, X-nav technologies, LLC, Lansdale, PA) that has been designed for implant placement uses tracking components that have hundreds of distinct tracking points. A few studies have evaluated the accuracy of this system in implant placement. In a model-based study, Emery *et. al.* evaluated the accuracy of dental implant placement using this system. Their investigation focused on measurement of overall accuracy for implant placement relative to the virtual plan in both edentulous (6 sites) and dentate (21 sites) jaw models. This study involved one surgeon experienced with dynamic implant placement using a dynamic navigation system (X-guide, X-nav technologies, LLC, Lansdale, PA) based on optical triangulation tracking. Virtual implants were placed into planned sites using the system. Post-implant placement CBCT scans were taken, superimposed (mesh overlaid) with the virtual plan and deviations from the virtual plan were determined. The angular accuracy of implants delivered using the tested device was $0.89^{\circ}\pm0.35^{\circ}$ for the dentate case type and $1.26^{\circ}\pm0.66^{\circ}$ for the edentulous model. 3D positional accuracy was 0.38 ± 0.21 mm for dentate cases and 0.56±0.17 mm for edentulous cases, measured from the implant apex. The authors suggested comparison of dynamic navigation to freehand placement in future studies (34).

In another study by Block *et al.*, platform and angle accuracy for dental implants using dynamic navigation was determined. This study involved three surgeons placing 100 implants in the mandible and maxilla of patients using the X-guide system. The system software has the capacity for planning the position of the implant by overlaying a picture of the desired implant on the CBCT scans. This implant is called a virtual implant. Virtual implants were placed using the system. Post-operative CBCT scans were taken, and superimposed (mesh overlaid) with the virtual plan and deviations were recorded. The results showed similar deviations to those reported for static tooth-based guides using literature references for comparison. Block *et al.* also demonstrated that the accuracy of the dynamic navigation was superior to freehand implant placement. A significant difference was found in accuracy between guided and freehand surgeries for all measured deviations ($p \leq 0.05$). There was no significant difference in accuracy between static and dynamic guided surgery methods. The three surgeons had similar accuracies after their learning curve was achieved. Proficiency, based on their case series studies was achieved by the 20th surgical procedure (35).

Another prospective study by the same group aimed at comparing the accuracy and precision of dynamic navigation with freehand (FH) implant fixture placement. Prospective data from 478 patients involving 714 implants which were placed with fully (FG) or partially guidance of dynamic navigation (PG) or free-hand method (FH) were evaluated. Differences in measurements comparing FG and PG navigation with FH indicated significantly less deviation from the virtual plan ($p \leq 0.05$) using navigation and they concluded that the use of this type of method results in smaller deviations from the planned placement compared with FH approaches (36).

Guided Endodontics

The concept of guided endodontics was first introduced by Krastl G. *et al*. in 2016 as a novel treatment approach for teeth with pulp canal calcification and apical pathology. A case report published by this group presented a successful attempt to negotiate the canal in a severely calcified maxillary incisor (27). They concluded that the presented approach is a safe and clinically feasible method to locate root canals and prevent root perforation in teeth with pulp canal calcification. The drills used in this report had a diameter of 1.5 mm and were unsuitable for the treatment of smaller-sized teeth such as mandibular incisors. Thus, an instrument with a diameter of 0.85 mm used for “Micro-guided Endodontics” in teeth with thin roots and in another case report, they showed successful preparation of minimally invasive access cavities for root canal localization in mandibular incisors with pulp canal calcification (30).

Accuracy of this static system, guided endodontics, has been evaluated in a couple of different studies. In an in-ex-vivo study by Zehnder *et al.*, sixty extracted human teeth were placed into six maxillary jaw models. Matching preoperative CBCTs with intra-oral scans using the coDiagnostic X TM software, access cavities, sleeves and templates for guidance were virtually planned and printed by a 3D printer. After access cavity preparation by two operators, a postoperative CBCT scan was superimposed on the virtually planned CBCT’s and accuracy was measured by calculating angle and deviation of planned and prepared cavities in three dimensions. All root canals were accessible after cavity preparation with

‘Guided Endodontics’. Deviations between the planned and prepared access cavities were low with means ranging from 0.16 to 0.21 mm for different aspects at the base of the bur and 0.17–0.47 mm at the tip of the bur. The mean angle of deviation was 1.81° (28).

In another study, the same group evaluated the accuracy of a miniaturized technique for apically extended access cavity preparations in anterior teeth. A specially designed drill with a diameter of 0.85 mm was used in this study. Sixty sound mandibular anterior teeth were used in ten mandibular models. Similar methodology was followed as Zehnder *et al.* above. Results showed that deviations between the planned and prepared access cavities were low, with means ranging from 0.12 to 0.13 mm for different aspects of the base of the bur and 0.12 to 0.34 mm at the tip of the bur. The mean angle of deviation was 1.59°. The mean treatment time, including planning and preparation, was approximately 10 minutes per tooth (29).

Another study was published in 2019 by the same group looking at guided endodontics versus conventional access cavity preparations to compare endodontic access cavities in teeth with calcified root canals prepared with one of the techniques regarding the detection of canals, tooth substance loss and treatment duration. They used six identical sets of four anterior upper and lower jaw models that had simulated calcified root canals. Templates for guided access preparation were fabricated based on 3D surface scans and CBCT data sets. Three operators with different levels of experience prepared access cavities on each tooth with either conventional or guided endo techniques (8 teeth per technique and operator). Access cavities were volumetrically assessed on postoperative CBCT scans and then compared statistically. Results showed that canal localization was successful in 41.7% of cases using the conventional technique and 91.7% with the guided approach. The mean tooth substance loss of conventional access and the guided approach was 49.9 mm^3 and 9.8 mm^3 respectively ($P<0.05$). The treatment lasted 21.8 minutes for the conventional technique and 11.3 minutes for the guided. Interestingly, the success of the guided approach was not influenced by the experience of the operator. They concluded that the guided method allows a more predictable and expeditious negotiation of calcified root canals with significantly less substance loss (39).

Studies regarding the use of dynamic navigation systems for guided endodontics are very limited. Only two studies, one by Chang BS *et al.* in 2019 (40) and the other one by Zubizarrera-Macho *et al.* in 2020 (41), investigated the use of computer-aided dynamic navigation. In the first study, 29 extracted human teeth were mounted in dental casts. A cone beam CT scan of each cast was taken with a radiographic marker attached and then imported into the planning software of a dynamic navigation implant surgery system (Claro Nav, Canada). Simulating implant surgery but for guided endodontics, the drilling entry and end points, angle, pathway, and the depth of the virtual drill were planned for all teeth. The cast was mounted in a phantom head and the radiographic marker was replaced. A drill tag was attached to the drill handpiece. Following calibration, drilling was done using the guided system and endodontic access cavity preparation was completed. Successful root canal location was confirmed using periapical radiographs and CBCT. Conservative access cavities were achieved and all the expected canals were successfully located in 26 out of 29 teeth. Due to tracking difficulties, only one canal was located in two maxillary second molars; in a maxillary first molar, only two canals were located and the access preparation for the third canal was misaligned and off-target. Accuracy including linear and angular deviations was not measured and reported. This study provided very limited information about feasibility of using these systems for guided endodontics.

In the second study, the accuracy of two computer-aided navigation techniques was compared with the conventional access procedure. A total of 30 single-rooted anterior teeth were selected and then randomly assigned into three experimental groups. In group A, the access cavity was made through a computer-aided static (template) navigation system (SN). In group B, the procedure was done through dynamic navigation system (DNS) (Navident, ClaroNav, Canada); while in group C, a freehand method (FH) was utilized for access cavity preparation. After endodontic access cavities were made, a postoperative CBCT was taken and the degree of accuracy between the planned and performed endodontic access cavities was analyzed using therapeutic planning software. Results showed no significant difference between SN and DN at the coronal, apical, or angular level; however, statistically significant differences were observed between the two navigation systems and the FH group (41). This study had a small sample size. Selected teeth didn't have canal calcifications. The drill for access cavity preparation had a diameter of 1.2 mm which was not very suitable for endodontic purposes. Drills with the diameter of ≤ 1mm are more desirable for endodontic purposes. Furthermore, no information is available on calibration and the learning curve of the operator for using the dynamic navigation system. Also, no head manikin or clinical simulation was done to mimic the clinical setting.

To date, the accuracy and efficiency of the X-guide dynamic navigation system have not been evaluated and other applications of dynamic navigation systems for access preparation, root canal localization, post removal, etc. have yet to be investigated.

Purpose

This study is the first to investigate the accuracy and efficiency of a dynamic navigation system (X-guide, X-Nav technologies, LLC, Lansdale, PA) for finding calcified root canals in single rooted human teeth in an ex-vivo model. The primary goal of this study was to compare the accuracy and efficiency of a dynamic 3D navigation system to a freehand method for locating calcified canals in human single-rooted teeth using an ex-vivo model. In this project, the following specific aims were pursued in both groups:

AIM 1: Evaluate accuracy (linear and angular deviations) of the drill path in different planes from the planned position.

AIM 2: Compare the time (efficiency) necessary for canal localization.

AIM 3: Compare the reduced dentin thickness at the CEJ and at an identified canal level.

AIM 4: Compare the frequency of perforations and unsuccessful attempts in canal identification.

Hypotheses 1

Null hypothesis: There is no significant difference in the accuracy of the Dynamic Navigation System (DNS) as compared to the freehand method (FH) in localizing the calcified canal of single-rooted human teeth.

Research hypothesis: The DNS system is significantly more accurate than the FH in localizing the calcified canal of single-rooted human teeth.

Hypotheses 2

Null hypothesis: There is no significant difference in the efficiency of DNS as compared to the FH in localizing the calcified canal of single-rooted human teeth.

Research hypothesis: The DNS system is significantly more efficient than the FH in localizing the calcified canal of single-rooted human teeth.

Hypotheses 3

Null hypothesis: In localizing the calcified canal of single-rooted human teeth, there is no significant difference in the reduced dentin thickness following the use of DNS as compared to the FH.

Research hypothesis: In localizing the calcified canal of single-rooted human teeth, the DNS system removes significantly lesser dentin than the FH.

Hypotheses 4

Null hypothesis: There is no significant difference in procedural accidents (perforation, ledge, transportation, and instrument fracture) frequency following the use of the DNS as compared to the FH in localizing the calcified canal of single-rooted human teeth.

Research hypothesis: The DNS system results in significantly fewer procedural accidents than the FH in localizing the calcified canal of single-rooted human teeth.

Materials and Methods

This study was an ex-vivo study on a natural tooth model. Sixty (60) de-identified human single rooted teeth (extracted in the prior six months for periodontal reasons) with narrow, partial or complete canal obliterations (identified by radiographic evaluation) were autoclaved and kept hydrated in distilled water prior to procedure. Maxillary and mandibular incisors and canines and mandibular premolars were used as test teeth. They were paired according to calcification status and then each pair randomly assigned into one two main experimental groups and then in each group, samples were randomly divided into two subgroups for two operators. Teeth in each group were mounted with Polyvinylsiloxane (PVS) impression material in dried maxilla and mandibles according to their anatomic positions to simulate partially dentate maxilla and mandibles. They were also splinted to each other with composite resin at the incisal third of their proximal surfaces to reduce any subtle movement during the experiment. An extra 40 single-rooted non calcified teeth were selected and used to calibrate the operators in the use of the x-guide system. Two additional maxillary and mandibular molars were placed on each side of the models to serve as recipients for X-clip fiducials as required by the DNS system and also for superimposition purposes.

There were two experimental groups in this study: 1) Dynamic 3D Navigation System (DNS), and 2) Freehand (FH) method. Two operators (one endodontic resident (OD) and one board-certified endodontist (AN)) planned the access cavity on preoperative CBCT scans of jaws on their randomly assigned teeth and performed FH or DNS methods based on the randomization process. Each operator performed both methods (DNS and FH) on 30 randomly selected previously matched teeth (N=15/ group) (Fig.4). FH group was finished first and DNS group was completed with a two-week interval. For reducing the setup cost of the DNS group, alternating each method and split-mouth model was not feasible. To decrease the chance of bias, operators were not involved in the accuracy evaluation. A board-certified radiologist (JP) calibrated a general dentist (research assistant (SA)) to perform CBCT scan measurements, alignment and superimposition. The statistician (ER) was also blinded to the experimental group information.

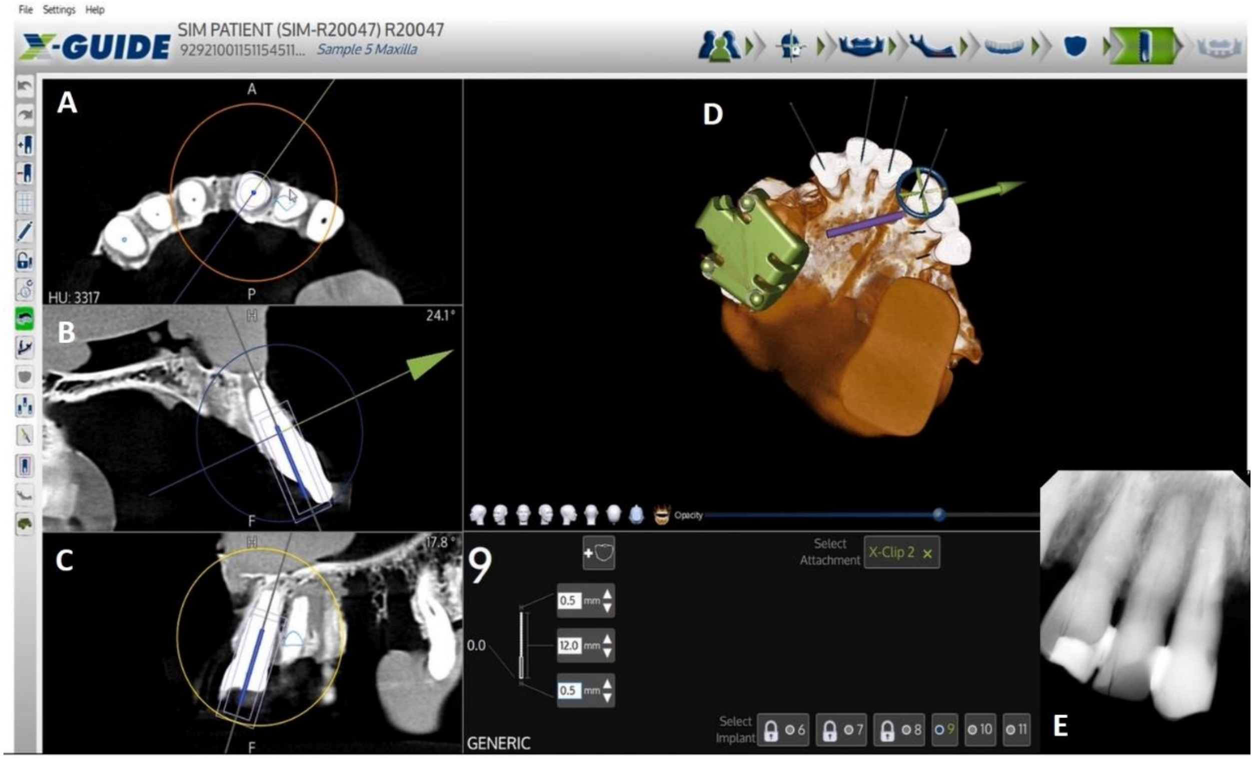
Scanning Protocol for both groups

Before acquisition of the CBCT, a small thermoplastic device (X-clip, X-Nav Technologies, LLC) with 3 radiopaque markers was molded to molars on one side of the arch (Left side for right-handed operator and right side for left-handed operator). This clip held the dynamic reference frames (DRFs) on the model during access cavity preparation in the DNS group. In the FH group, an X-clip was placed on each model similar to the placement in DNS group to facilitate preoperative and postoperative CBCT superimpositions. To measure the accuracy parameters, a CBCT scan (CS 9300, Carestream LLC, Atlanta, GA) was taken for both groups after the X-clip placement at a 0.090 voxel resolution by school radiology technicians.

Access cavity planning for both groups

The DICOM data set from the CBCT of both groups was uploaded to the X-guide software and entered into the DNS planning system. Then planning software was used to plan the access cavity drilling entry point, angle, pathway, and the depth needed to localize canals based on the CBCT data sets (Fig. 1). This process was similar to implant placement planning with the DNS software. However, for endodontic purposes, a 0.5 mm drill template served as the guiding path for the drill during the procedure.

Fig. 1. This figure shows an example of planning software used by the operators to plan the access cavity preparation on tooth #9. The drilling path is seen in three different planes. A, Axial; B, Sagittal; C, Coronal; and D, is a 3-dimensional rendering including the green X-clip in place. E presents a periapical radiograph of tooth numbers 9,10, and 11.



Access cavity preparation for both groups

For performing the access cavity procedure, each jaw was mounted onto a dental manikin. A latex face with limited mouth opening was used to simulate limited visibility and pressure due to facial soft tissues. In the DNS group, access cavities were made under full guidance of the X-guide system. For initial set up, both handpiece and dental models required dynamic reference frame (DRF) systems (tracking arrays) and calibration to be identified. Calibration of the handpiece and dental models was done based on the manufacturer's recommendation prior to initiating treatment. Handpiece calibration determined the relationship between the geometry of the handpiece tracking array and the axis of the drill. Jaw calibration related geometry of the ‘patient tracking array’ to the CT fiducials, therefore providing a link between the preoperative planning system and a trackable coordinate system. The stereo tracking system consisted of two cameras that simultaneously triangulate each tracking array to navigate the precise position and orientation of the handpiece and head position. The dental model DRF included the X-clip which was connected to the ‘patient-tracking cylinder’. The X-clip was placed on the molars in the same position as it was when the CBCT image was taken. The tracking software algorithm triangulated the two arrays continuously and live video allowed the operators to get virtual feedback from the navigation system to visualize site preparation (Fig. 2,3). When the handpiece approached the selected tooth, a virtual image appeared on the system display. Also, a target with crosshair reticule and depth gauge and angle information appeared on the system display.

In the FH group, preoperative CBCTs were reviewed and an access cavity was made freehand under a dental operating microscope following the virtual planned path using the same type of drill as in the DNS group. First, enamel was removed with a diamond bur until the dentin was exposed. Next, Mounce burs at 5000 RPM were used (size 2, to CEJ level and then size 1 to the end of drilling point) in both groups. The burs were cleaned regularly during preparation using a sterile sponge. The access cavity process was finalized when the final bur reached the end of the planned drill path in the DNS group and when the canal was located and confirmed in the FH group by each operator with a periapical radiograph with a #10 or #15 K-file to an estimated working length. The burs were replaced after each access preparation. Following access preparation in both groups, a second postoperative CBCT scan was taken by one of the dental school radiology technicians with similar exposure parameters as the preoperative CBCTs.

Fig. 2. Schematic view of the 3D dynamic navigation system configuration. CBCT Dicom data was imported to DNS planning software. One tracker (Patient position tracker) was attached to model's jaw through the X-clip fiducial mounted on molars and the second tracker was attached to the dental handpiece. Blue arrow shows the X—clip in place.

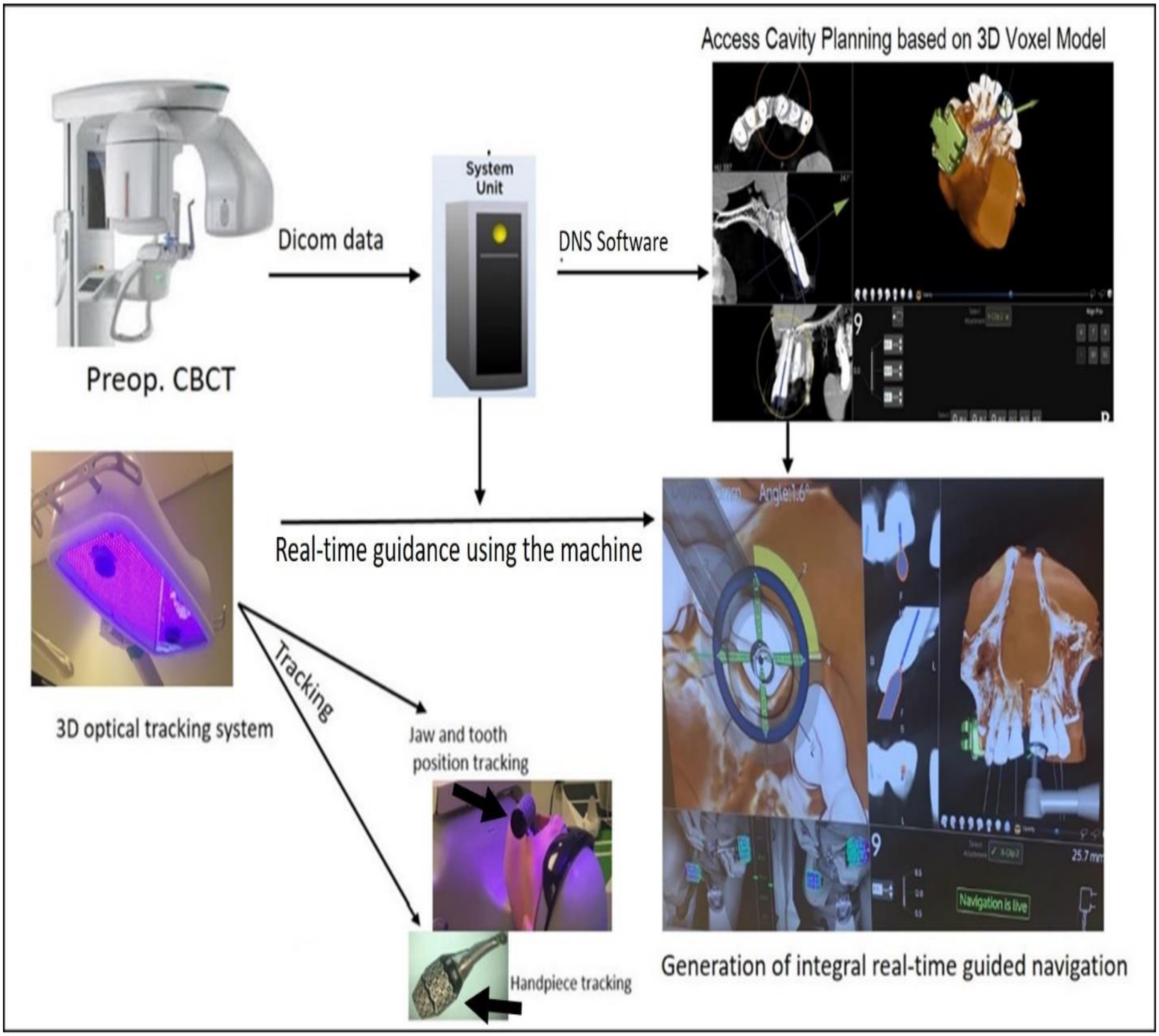


Fig. 3. The stereo-tracking system is indicated by the red arrow. Trackers were attached to the model’s jaw through the x-clip fiducial mounted on the molars and on the dental handpiece (Blue arrows).

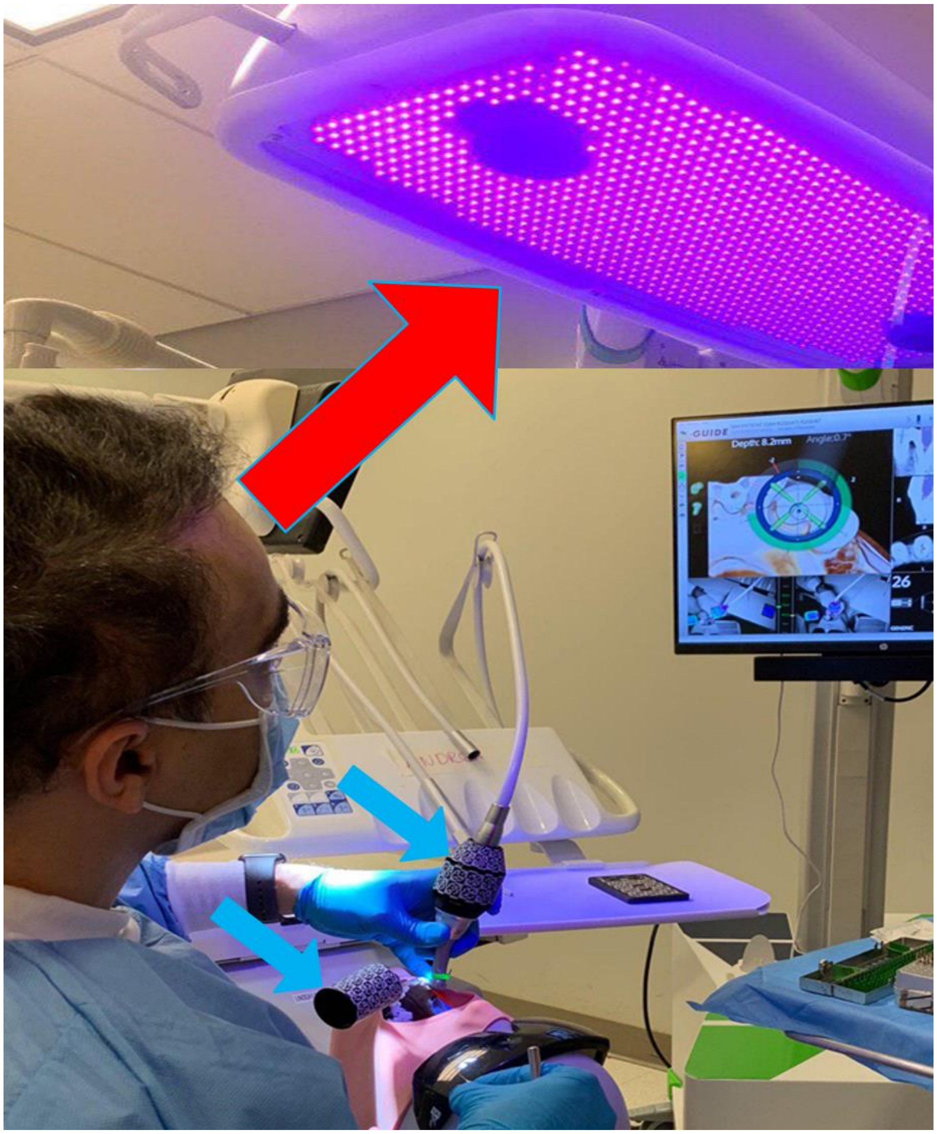
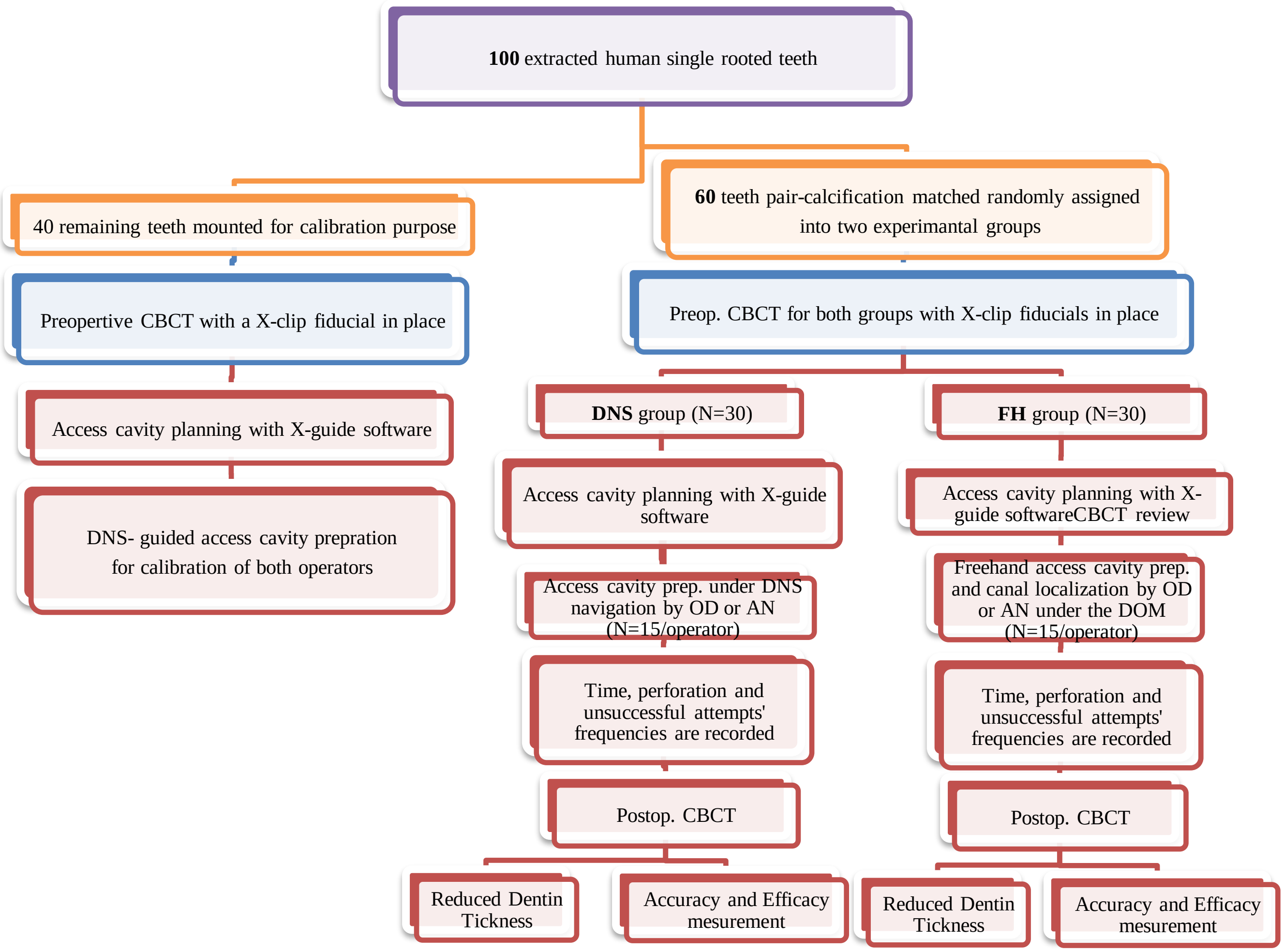


Fig 4. Flowchart of experimental protocol.



DNS: Dynamic Navigation System; FH: Freehand; DOM: Dental Operating Microscope,

Preop.: Preoperative; Postop.: Postoperative.

Data collection

Accuracy was evaluated by (SA) measuring and comparing the variables on both the preoperative virtual plan and the postoperative CBCT scans. Lateral and angular deviations of the prepared access cavities from the planned position was quantified (as described below).

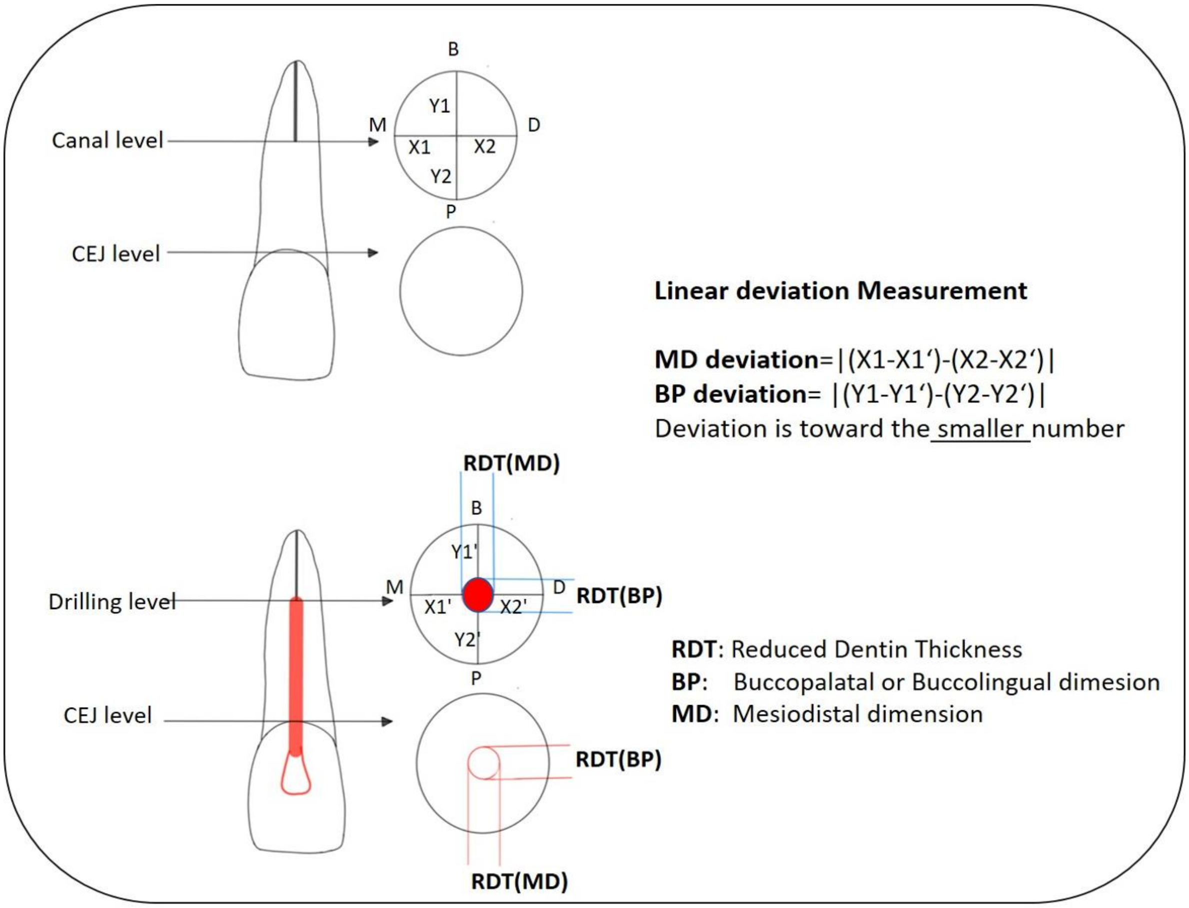
The process for evaluating accuracy was as follows:

1) Drill path and prepared access cavity for both DNS and FH were identified in postoperative CBCT scan.
2) Accuracy metrics between the planned and prepared access cavities in both groups were computed:
    1) Linear deviation (mm): difference on CBCT scans between the planned and prepared access cavities at the end of the drill in mesial/distal (x-axis) and buccal/lingual (y-axis) dimensions of axial sections (Fig.5)
    2) Reduced dentin thickness was measured at the CEJ and drill end level in mesial/distal and buccal/lingual dimensions in the axial sections of the postoperative CBCT scan.
    3) Angular deflection (degree): difference between the angle of planned and prepared access cavity by superimposition of preoperative and postoperative CBCT scans.

The duration of access cavity preparation after the enamel removal step to the point of successful negotiation was recorded with a stopwatch.

If any perforation happened, the procedure was considered terminated after the perforation was verified by a radiograph. Perforation frequency was recorded. The site of the perforation was also verified using the postoperative CBCT. Finally, the number of unsuccessful attempts in canal negotiation and other complications (ledge formation, transportation, instrument fracture, etc.) during canal negotiation in both groups was recorded.

Fig 5. Schematic view of calculation method for linear deviation and reduced dentin thickness (RDT).



Power and Data Analysis

Sample size calculation

An N of 5 was used in the pilot study to determine the number of subjects needed for the actual study. With 2 groups, a $p \leq 0.05$, a mean for DNS= 1.14 and for FH 1.51, an effect size of 0.33 and power of .80, an N of 30 in each group was required. For efficiency, power was 100% with an N=5.

Statistical analysis was done using SPSS 25.0 (SPSS Inc, Chicago, IL) software. In this experimental study, descriptive statistics (including the mean and standard deviation) for all dependent variables was calculated. Assumptions of equality of variances and normal distribution of errors were checked. Considering normal distribution of data (Shapiro-Wilk test), the mean values of deviations, reduced dentin thickness and time were compared by one-way ANOVA between the groups. Frequency of perforations and unsuccessful attempts in each group were compared using χ^2.

Results

Baseline Data

In this ex-vivo natural tooth model study, 30 calcified single rooted teeth were included in each group. The mean required drilling depth in DNS and FH groups were 12.59 ± 1.93 mm and 11.75 ± 1.65 mm respectively with no statistically significant difference (p>0.5) (Table 2). Table 3 shows characteristics of included specimens in each group/subgroup.

Table 2. Summary of calcification depth in two experimental groups.

	DNS	**FH**	**p. value**
Calcification depth	12.59±1.93	11.75±1.65	NS

NS: Not statistically significant

Table 3. Characteristics of included samples in two experimental groups and four subgroups.

Experimental groups	**Calcification category**		**Min**	**Max**	**Calcification depth** (Mean±SD)	**Maxillary teeth**	**Mandibular teeth**
	9-13 mm	>13 mm					
DNS- (OD)	8	7	10.9	20	13.22 ± 2.14	6	9
DNS-(AN)	9	6	9.5	14.6	11.96 ± 1.52	6	9
DNS-Total	17	13	9.5	20	12.59 ± 1.93	12	18
FH- (OD)	9	6	9.1	14.9	11.44 ± 1.57	6	9
FH-(AN)	9	6	9.1	15.1	12.06 ± 1.70	7	8
FH- Total	18	12	9.1	15.1	11.75 ± 1.65	13	17

The mean linear deviation for both operators using the DNS approach was 0.19±0.21 mm and 0.12±0.14 mm in BL and MD directions respectively and for the FH technique was 0.81±0.74 mm in BL direction and 0.31±0.35 mm in MD direction. In BL direction, the DNS group showed significantly less deviation than FH group (P≤0.001) (Table 4). Table 5 presents details of deviation in BL and MD directions divided by operators and in total for both techniques.

Table 4. Linear deviation of two experimental groups in buccolingual and mesiodistal directions.

	DNS	**FH**	**p. value**
BL	0.19±0.21	0.81±0.74	p≤0.001
MD	0.12±0.14	0.31±0.35	NS.

BL: Bucco-lingual, MD: Mesio-distal

Table 5. Linear deviation of two experimental groups completed by 2 operators in buccolingual and mesiodistal directions.

Experimental groups	**Linear deviation**					
	BL			**MD**		
	min	max	Mean±SD	min	max	Mean±SD
DNS- (OD)	0.01	0.45	0.17±0.19	0.01	0.52	0.14±0.14
DNS-(AN)	0.08	0.88	0.21±0.23	0.01	0.47	0.10±0.13
DNS-Total	0.01	0.88	0.19±0.21	0.01	0.52	0.12±0.14
FH- (OD)	0.01	2.49	0.66±0.65	0.0	1.4	0.36±0.40
FH-(AN)	0.02	2.28	0.95±0.85	0.01	1.25	0.25±0.30
FH- Total	0.0	2.48	0.81±0.74*	0.0	1.4	0.31±0.35

BL: Bucco-lingual, MD: Mesio-distal

The mean angular deflection as reflected in table 4-1 was 2.39±0.85º degree in DNS group, whereas it was 7.25±4.2º in FH group. One-way ANOVA showed a statistically significant difference between two experimental groups (p≤ 0.0001) (Table 6). In table 7, the measurements of four subgroups can be found.

Table 6. Angular deflection in two experimental groups.

	DNS	FH	p. value
Angular deflection	2.39±0.85º	7.25±4.2º	p≤0.0001

Table 7. Angular deflection of drill path compared to virtual planned path in two experimental groups completed by 2 operators.

Experimental groups	**Angular deflection**		
	min	max	Mean±SD
DNS- (OD)	0.8º	3.2º	2.08±0.65º
DNS-(AN)	0.9º	4.6º	2.70±0.93º
DNS-Total	0.8º	4.6º	2.39±0.85º
FH- (OD)	2.5º	19.3º	7.09±4.38º
FH-(AN)	3.0º	17.7º	7.41±4.22º
FH-Total	2.5º	19.3º	7.25±4.2º *

Regarding the reduced dentin thickness at CEJ level, the DNS group resulted in significantly less dentinal removal compared to the FH group (1.06±0.18 mm vs. 1.55±0.55 mm; p≤0.0001). At the end of the drill, the same finding was observed between two groups and reduced dentin thickness in the DNS group was significantly less than the FH group (1.18±0.17 mm, 1.47±0.49 mm; p≤0.001) (Table 8). Table 9 shows the details of reduced dentin thickness measurements in different subgroups.

Table 8. The average reduced dentin thickness of two experimental groups at two levels.

	DNS	FH	p. value
CEJ	1.06±0.18	1.55±0.55	p≤0.0001
End of the drill	1.18±0.17	1.47±0.49	p≤0.001

Table 9. Reduced dentin thickness at CEJ and end of the drill levels in two experimental groups completed by 2 operators in buccolingual and mesiodistal directions.

Experimental groups	**Dentin Reduction (mm)**			
	CEJ		**End of the drill**	
	BL (Mean±SD)	MD (Mean±SD)	BL (Mean±SD)	MD (Mean±SD)
DNS (OD)	1.08±0.11	1.06±0.14	1.19±0.10	1.07±0.17
DNS (AN)	1.13±0.2	0.99±0.23	1.26±0.09	1.19±0.25
DNS- 2 operators	1.10±0.16	1.02±0.19	1.22±0.10	1.13±0.22
DNS- Average total reduction	1.06±0.18		1.18±0.17	
FH (OD)	1.57±0.62	1.17±0.36	1.87±0.60	1.16±0.27
FH (AN)	2.06±0.50	1.40±0.21	1.67±0.33	1.19±0.26
FH- 2 operators	1.82±0.61	1.29±0.31	1.77±0.48	1.18±026
FH- Average total reduction	1.55±0.55*		1.47±0.49*	

CEJ: cementoenamel junction, BL: bucco-lingual, MD: mesio-distal

Location and negotiation using DNS were achieved in 29 of 30 root canals (96.6%). One unsuccessful attempt in DNS group happened in a canine tooth with a totally calcified canal and a nonvisible canal neither on the periapical radiograph nor CBCT scan. Sectioning at the end of drilling path confirmed full calcification with no clinical evidence of canal presence under dental operating microscope. Using the conventional FH technique, 25 out of 30 root canals were accessed and localized (83.3%) ($p>0.05$). On the other hand, five unsuccessful attempts in the FH group resulted in perforation. In addition 3 more transportations noted in the FH group and χ^2 test did show a significant difference between the two groups in regard to procedural error rate. The mean duration of time required for canal localization was significantly less in the DNS group compared to the FH group ($p<0.05$) (Table 10). Also, the difference between two operators in the FH group was statistically significant ($p<0.05$) Table 11 summarizes the results divided by two operators regarding successful localization, complications, and treatment duration for both experimental groups.

Table 10. Treatment duration, successful attempts and complications in two experimental groups

	DNS	**FH**	**p. value**
Treatment duration	227±97	405±246	p≤0.05
Successful attempts	29	25	NS.
Procedural errors	1	8	p≤0.05

Table 11. Time required for access cavity preparation, successful attempts frequency and mishaps in two experimental groups and four subgroups.

Exp. Group	**Mean Time**	**Min**	**Max**	**Successful Attempts**	**Perf.**	**Trans.**
DNS-(OD)	244±112 sec. (4', 4")	148 sec. (2', 28")	600 sec. (10')	14/15	0	1
DNS-(AN)	210±80 sec. (3', 30")	91 sec. (1', 31")	360 sec. (6')	15/15	0	0
DNS-Total	227±97 sec. (3', 47")	91 sec.	600 sec.	29/30	0	1
FH-(OD)	568±248 sec. (9', 28")	240 sec. (4')	1140 sec. (19')	13/15	2	2
FH-(AN)	242±83 sec. (4', 2")*	84 sec. (1', 24")	364 sec. (6', 4")	12/15	3	1
FH- Total	405±246 sec. (6', 45")*	84 sec.	1140 sec.	25/30	5	3

Perf.: perforation, **Trans.**:transportation, **sec.**: seconds

Figures 6,7 present two samples in the DNS group with minimum reduced dentin thickness and deviations. Figures 8,9,10 demonstrate three cases in the FH group with different outcomes.

Fig 6. A DNS group sample. **A,B,** preoperative sagittal and coronal sections of #20 with a calcified canal. **C,D,** postoperative views show minimum RDT and linear deviations.

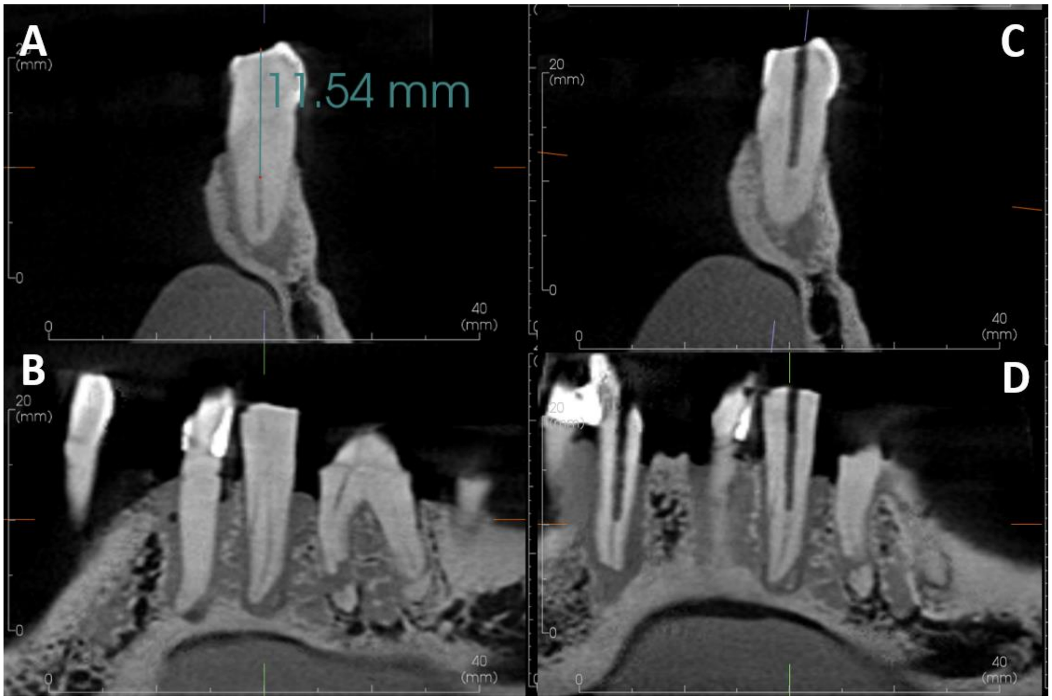


Fig 7. Another DNS group sample. **A,B,** preoperative sagittal and coronal sections of #9 with a calcified canal and internal resorption. **C,D,** postoperative views show minimum RDT and linear deviations.

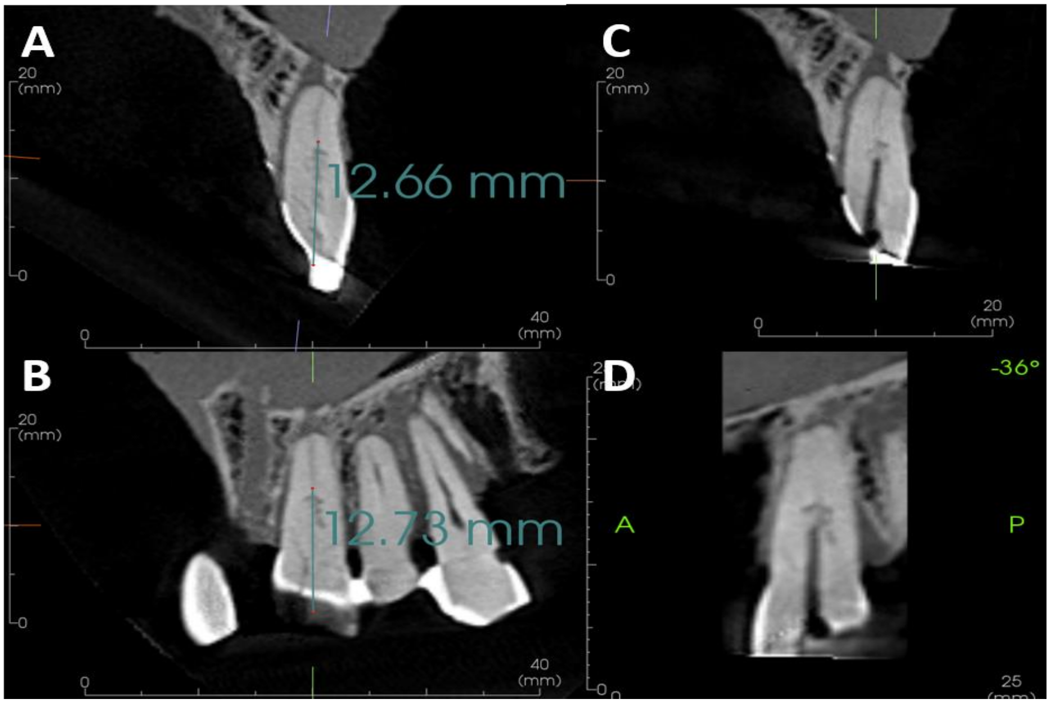


Fig 8. A FH group sample. **A,B,** preoperative sagittal and coronal sections of #6 with a calcified canal. **C,D,** postoperative views show minimum linear deviation.

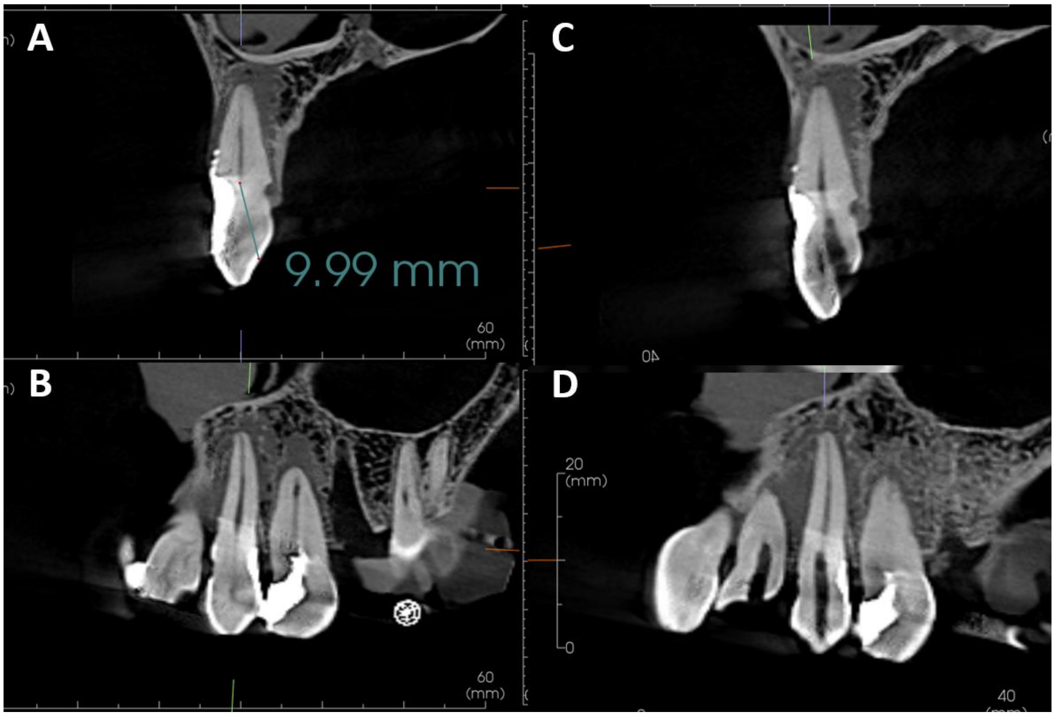


Fig 9. The second FH sample. **A,B,** preoperative sagittal and coronal sections of #12 with a calcified canal. **C,D,** postoperative views show significant BL and minimum MD deviations.

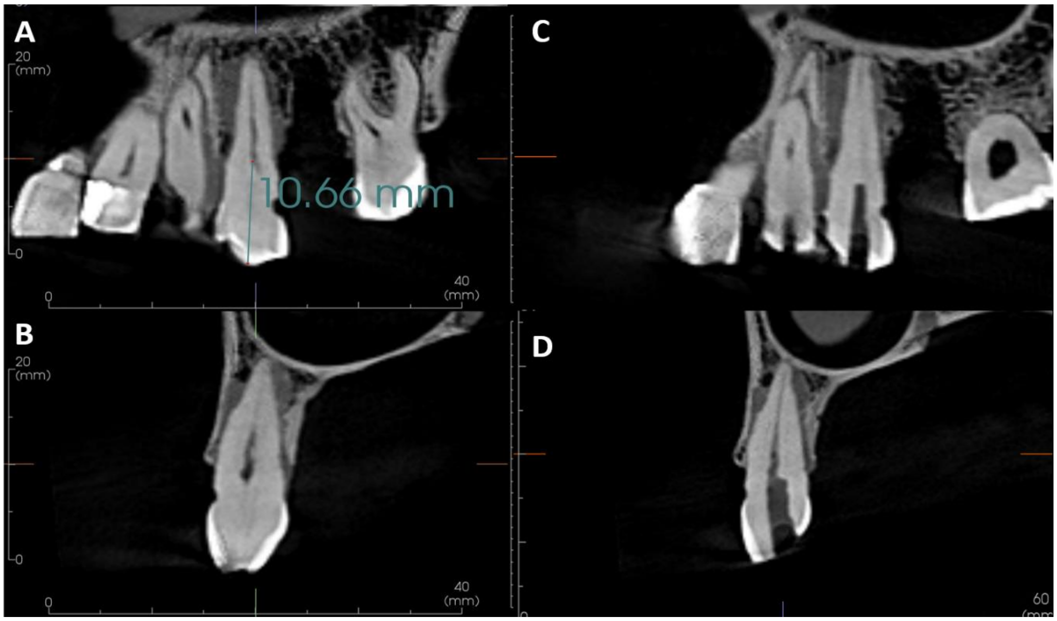
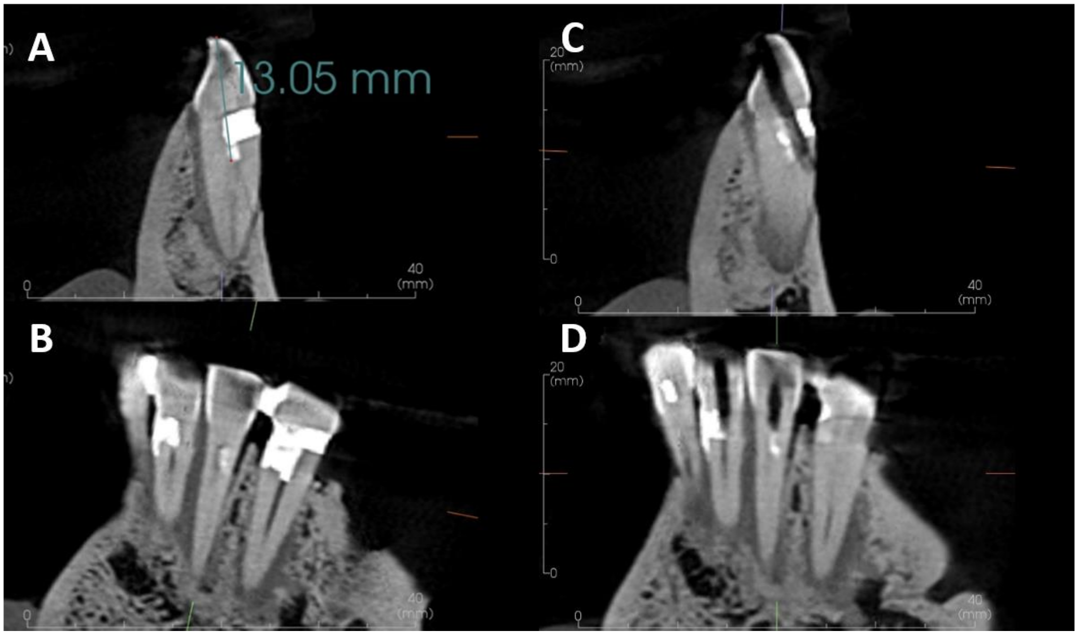


Fig 10. The third FH sample. **A,B,** preoperative sagittal and coronal sections of #23 with a calcified canal. **C,D,** postoperative views show an unsuccessful attempt and the buccal perforation.



Discussion

Accuracy and precision in access cavity preparation and successful localization of canals in endodontic cases with calcified root canal systems are very important especially when we are treating teeth having minimum dentin structure such as mandibular incisors. This appears to be the first study comparing both the accuracy and efficiency of a Dynamic Navigation System to a conventional Freehand method for negotiating calcified canals in a natural tooth model. In this ex-vivo experimental study, we included 30 calcified single rooted teeth with a drilling depth of more than nine mm in each group. The mean required drilling depths were 12.59±1.93 and 11.75±1.65 in the DNS and FH groups respectively. Therefore, all cases were categorized as moderate or high difficulty based on AAE difficulty assessment (17). The results obtained in the present study reject the null hypothesis (H_o) and show that the X-guide system (X-Nav, USA) outperforms the conventional FH CBCT-approximated approach using DOM and CBCT-approximated methods in terms of both accuracy and efficiency. This system has the potential to reduce the linear and angular deviations of the drill during access preparation, dentin removal both at the CEJ level and inside the canal, intra-operative time as well as complications such as perforation and transportation. The results showed improved performance in angular deflection and linear deviation especially in the BL direction, but also in MD direction. The dentin reduction was 1.18±0.17 and 1.47±0.49 mm in DNS and FH groups respectively at the end of the drill ($p \leq 0.05$). Lower standard deviation of data in the DNS group showed more consistency and reproducibility of the method as compared to the FH method. However, the efficacy of this system in managing difficult calcified molar cases yet needs to be investigated. Also, feasibility and efficiency of using the system in combination with conventional technique (initiating the treatment with conventional method using DOM and then utilizing the DNS system for managing the challenging calcified canal in molar endodontics) should be evaluated in a future study.

Although the most clinically relevant parameters analyzed in this study were angular and apical linear deviation and reduced dentin at the end of the drill, using deviations and dentin reduction as the only measurements can be misleading because they do not indicate their clinical importance or relevance. In another word, there is no standard or cut-off point for determining the acceptable range of deviations or dentin removal. Ideally, the clinician goal is to achieve 0 mm of linear deviation, 0º of angular deflection and the lowest amount of dentin removal but is not always clinically possible. In addition, the importance of these variables might not be equal in teeth with different dentin thickness. Another variable that may provide useful information regarding the system performance is volumetric analysis of the prepared access spaces in both groups. Since the teeth were not completely matched based on their type, size and calcifications depth, this analysis was not executed. Further studies using identical 3D printed teeth can be designed and performed to evaluate this factor as well. Instead, three other clinical factors were added and analyzed in this research: the required time for localizing the canal, success rates of finding the canal, and complication rate.

Regarding efficiency, the average time for localizing the canal in the DNS group was 227 seconds, while this number was 405 seconds in the FH group ($p \leq 0.05$). A success rate of 96.6% was found in the DNS group while the FH group was 83.3% successful. In addition, drilling resulted in five perforations and three large transportations in the FH group and no perforations or transportation in the DNS group. Although the successful attempts didn't show any statistical differences between the two groups, they are clinically important. However, the number of procedural errors between two groups showed a significant difference. Therefore, this tested DNS system can assist the clinician in locating the canals safer and in a shorter period of time. Therefore, it is more efficient. However, it must be mentioned that the time needed for virtual planning, machine set-up as well as calibration were not been calculated and recorded in this study. Also, it should be mentioned that both operators in this study were experienced in the FH method, which might have biased the results in the FH group. In addition, teeth used in this study were single-rooted teeth with an intact crown or minimal restorations and therefore the required time needed to locate the canal in this study does not reflect the actual time that might be needed in conventional clinical setting. Further studies using clinicians with more diverse skills and experience levels and more difficult cases (access through the crown and calcified molars) should be explored.

In the current study of accuracy measurements, cone-beam CT technology was used, and preoperative and postoperative scans were analyzed. Micro-CT scans provide more precise and accurate data analysis of accuracy but taking micro-CT scans of a full jaw was not practical in this study because of the machine limitation on sample dimensions. Furthermore, for both the dynamic navigation and the free-hand group, CBCT scans were still needed. Therefore, it was decided not to add micro-CT scans for measurements since this increased the budget without providing any significant benefit.

The use of endodontic microscopy and ultrasonic tips to access obliterated root canals has allowed clinical success rates of approximately 74% (42). It is well-known that even with the use of the dental operating microscope (DOM) in negotiating of extremely calcified root canals, there is a high risk of deviation, perforation, or at least higher tooth loss and overpreparation of the root canal space (42). As mentioned before, to increase such rates and at the same time to provide a more conservative and faster approach, a new technique, namely guided endodontics was introduced (27). Previous studies confirmed the accuracy of CBCT-guided static models to locate and negotiate calcified canals and maximum conservation of the coronal and radicular tooth structure along with a reduced deviation and risk of root perforations within a shorter time (28-30). A few case reports showed high success rate with the static guide technique in cases with different degrees of canal calcification (27,43,44). The main benefit of static over dynamic guides is that the operator can't deviate from the planned path. This facilitates treatment even by inexperience operators. This finding was confirmed in a study by Connert at al. (2019) (39). In addition, static guides are still more accessible worldwide. On the other hand, if the template does not fit properly, the treatment must be delayed. This introduces a limitation to the procedure in which nothing can be changed or modified once the template is fabricated.

Two studies by Zehnder et al. and Connert et al. (28,29) which looked at the accuracy of static guides for guided preparation have shown linear deviations ranged from 0.12-0.13mm and 0.16-0.21 mm at the base of the bur and 0.12-0.34 and 0.17-0.47 mm at the tip of the bur and mean angular deflections of 1.59º and 1.81º. The findings of the DNS group in this study were comparable to these two studies in regard to linear deviation. However, the mean angular deflection in our study was 2.39 º which was higher than the other two.

DNS has the potential to provide important advantages over the static approach including: 1) ability to do the entire procedure (CBCT, planning and treatment) in a single appointment, 2) increased safety and predictability due to the ability to verify the guidance accuracy at any time by a simple system check, 3) simple and faster planning, 4) improved irrigation, reducing the risk of tooth structure damage because of overheating, 5) more importantly, guidance is possible when interocclusal or interdental space is limited since a physical template is not necessary. Although two case reports have shown possibility of using a static guide in posterior areas (45,46), the dynamic navigation technology seems more practical/feasible for posterior teeth than static guides. Further study should be done to evaluate the accuracy of DNS system for access cavity preparation of calcified molars.

There are three types of errors related to dynamic guided systems: machine-inherent, patient or tooth-inherent and operator-inherent. Any looseness or "play" in tracking components could further impact the accuracy. These include but were not limited to 1) unstable seating of the X-clip, 2) rocking movement of the jaw attachment and 3) eccentric movement of the drill relative to the handpiece handle being tracked. The good point about this type of error is that it can be detected by the system check before and during the procedure and can be corrected on site. All attachments can be tightened, and the rocking movement of the X-clip connection can be fixed using a rigid bite registration material like blue mousse. Patient and tooth-inherent factors are those which stem from the patient or the tooth being treated. Patient movement during CBCT acquisition and presence of radiopaque coronal restorations like full coverage crowns, amalgam and large composite restorations can affect CBCT image quality and impede the virtual planning accuracy and eventually the procedural accuracy.

Presence of tooth mobility can also introduce another source of inaccuracy. In the present study, the samples were completely still during CBCT acquisition. Also, X-clips were left in place once inserted that decreased any possible error that might be caused due to X-clip instability or removal and re-insertion. In addition, teeth were splinted to each other by resin composite to reduce any errors that might have occurred due to tooth movement during the procedure. The above-mentioned factors can be precisely controlled in an ex-vivo experiment to produce results that are more accurate that in the clinical setting. Not surprisingly, based on previous implant studies, deviations measured in clinical studies can be significantly higher. Therefore, clinical studies are still warranted to evaluate accuracy and deviation measurements.

Regarding operator-inherent errors, the clinician’s control of the handpiece is not always consistent/perfect because of within-individual variability of motor control and hand-eye coordination. Even if a guided approach is used, some authors consider it a guided FH method, meaning that there is a space for clinician errors by their not following the virtual plan and therefore causing deviation. Thus, use of a manually controlled operation adds an element of operator-dependent error irrespective of the accuracy that may be inherent in the technology itself. Maintaining the proper angulation, path, depth and controlling the handpiece requires a certain level of skill, hand-eye coordination and manual dexterity, which necessitate a learning curve. The learning curve for using this machine has been shown to be important in a clinical trial by Stefanelli et al. (47). They concluded that the experience level of the surgeon with the dynamic navigation appears to improve the accuracy and the outcome. They found a significant improvement in mean linear and angular deviations between the first and the final 50 implant surgeries (47). Also, Emery et al. recommended 20 trial attempts for learning and calibration before surgical attempts on real patients (34). In the current study, both operators practiced this technique for 20 cases before study began.

The main disadvantage of DNS is the difficulty looking at the system display during the procedure instead of direct vision on patient or through the dental operating microscope. Application of augmented reality devices and head-mounted displays in addition to DNS systems can be helpful in transferring and overlaying the virtual plan on the patient jaw and teeth. This can provide the benefit of not losing the track of operation/treatment field and also possibility of using a 3D-microscope for magnification (48). Another limitation is the presence of a bulky handpiece attachment which makes it uncomfortable for routine use. Some companies have come up with ideas like laser printing of the DRFs (Dynamic reference frames) on the handpiece body or some modifications in the attachments design to make it easier to grip. The accuracy of those machines should be evaluated in separate investigations. The relatively high cost of the machine and the extra charge for the X-clip/procedure can be another limiting factor in widespread use of this technology. However, with the emergence of advanced technologies such as augmented reality and design modifications, some reduction in the overall cost of using this technology can be expected in the near future. Also, if this technology proves to save significant time in the clinical setting and prevent iatrogenic mishaps, even with the current cost, it is justified for use in the clinical setting. Finally, for using the machine and proper X-clip positioning that doesn’t interfere with the procedure, a full-arch CBCT is needed in most cases that will result in increased patient radiation compared to a limited field of view CBCT scan.

Limitations and future direction

This study was one the first studies to look at the accuracy and efficiency of one of the available DNS systems in the market. It was an ex vivo study and many confounding factors were controlled. However, clinical studies should be implemented to evaluate the system accuracy in the clinical setting. Sample size was limited to 30 cases in each group because of difficulty in collecting teeth having required inclusion criteria.

Both operators in this study had more than five years of clinical experience in endodontics. Therefore, no difference was found in their performance except the required time to localize the canal in the conventional freehand group which was shorter for the board-certified endodontist than the endodontic resident. Further studies are needed with operators who have more pronounced variations in clinical experience.

Lastly, the DNS machine used in the study still has many limitations and the manufacturer should work to address 1) bulky attachments, 2) the cumbersome setup and 3) the software, not designed for endodontic purposes but for implant placement. Software update adding endodontic module is very necessary for moving forward in the use of technology. Designing smaller handpiece- and jaw-tracking attachments are warranted for easier use of the technology for endodontic purposes. Also, modification of the X-clip and jaw tracking sensors in such a way that navigation becomes feasible with the use of a smaller field of view CBCT scans is needed.

The possibility of attaching different types of handpieces, including high-speed, slow-speed and ultrasonic, may provide many benefits for surgical and non-surgical guided endodontics.

Integration of augmented reality devices and head-mounted displays can be helpful to transfer and overlay the virtual plan on the patient jaw and teeth. It can provide the benefit of not losing track of operation field.

Last but not the least, trials should be designed and implemented to determine accuracy, efficiency and predictability in the clinical setting and to improve system accuracy and overcome its limitations.

Conclusion

In conclusion, within the limitations of this ex-vivo study, guided endodontics using the dynamic navigation system resulted in more accurate and efficient localization of calcified root canals with significantly less reduced dentin structure compared with conventional endodontic access using DOM and CBCTs. Dynamic navigation seems to be a safer and faster technique even for an experienced endodontist than conventional access cavity preparation. However, addressing the system limitations and clinical trials are warranted before its widespread clinical application.

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