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Achieving Dentin Conservation using Dynamic Navigation Technology for Locating Calcified Canals

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Dentistry at Virginia Commonwealth University.

by

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Abstract

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Purpose: Pulp canal obliteration (PCO) is a common sequela of dental trauma, caries, restorations and vital pulp therapy procedures. Despite the application of high magnification and CBCT imaging, access cavity preparation for such cases is prone to procedural errors that may lead to substantial loss of dentin structure thereby reducing the long-term prognosis. This study aimed to achieve dentin conservation using a novel computer assisted dynamic navigation system (Navident) in comparison to freehand access preparation for locating calcified canals.

Methods: Forty maxillary and mandibular central incisors (tooth #9 and tooth #25) were 3-D printed to simulate PCO. They were randomly assigned to the following treatment groups – Group 1: Freehand access; Group 2: Dynamic navigation access. Successful location of the canal, perforations and treatment times were noted, and volumetric analysis of remaining tooth structure was performed utilizing ITK-SNAP open source segmentation.

Results: The access treatment method (freehand vs dynamic navigation) did not result in a significant difference in perforations or ability to locate the canal. Dynamic navigation resulted in significantly less tooth structure removed in maxillary teeth (35.5 vs. 62.2, p-value<0.05), but the difference was negligible for mandibular teeth (19.0 vs 19.1, $p>0.05$). Dynamic navigation was associated with significantly faster drilling times for the first 8 treatment attempts in maxillary teeth ($p<0.05$). By the ninth attempt, the time was not significantly different between the two treatment methods ($p>0.05$). The time was not significantly different between freehand and dynamic navigation for any of the treatment attempts in mandibular teeth ($p>0.05$). Drilling time significantly improved across the attempts for the freehand method in maxillary teeth by an average of 52.4 seconds per attempt ($p<0.05$) but was not significant for any of the other treatment groups.

Conclusion: This study demonstrates the potential of applying dynamic 3-D navigation technology to preserve tooth structure and predictably locate root canals in teeth with PCO.

Introduction

Access preparation is one of the most important tasks in root canal therapy as this step sets the stage for the entire procedure. The main objectives of an endodontic access include, but are not limited to: removal of caries, removal of pulp tissue within the pulp chamber space, removal of the pulp chamber roof and any pulp horns, location of the canal(s), straight-line access to facilitate endodontic instrumentation with minimal obstruction in the coronal region of the root canal space and to conserve as much tooth structure as possible. An experienced operator will be able to locate the root canal spaces in most cases; however, there are many clinical cases that are more complex than others. Clinical situations that are particularly more advanced include those in which the root canal space is calcified or obliterated. This is often the result of stress in which pulpal responses ensue and will often alter the internal canal anatomy.

Pulp canal calcification or obliteration (PCO) commonly occurs as a result of trauma and most often affects the anterior teeth of young adults. PCO may also result from any of the following: caries, placement of restorations (1,2), vital pulp therapy procedures (3,4) and apposition of secondary and tertiary dentin over time (5,6). PCO occurs in 15 to 40% of patients following luxation injuries (7–9). The severity of the luxation injury and the stage of root formation determines the frequency of PCO (10). PCO is considered a sign of pulp vitality, thus root canal treatment is not indicated unless clinical or radiographic signs of pulp necrosis become evident which occurs in approximately 7-27% of PCO cases (8,11–13).

Although a tooth may exhibit evidence of complete radiographic obliteration, this does not indicate an absence of the pulp or canal space. Although histologic specimens of teeth with PCO typically present a persisting narrow root canal (14), determining the correct location of the root canal can be difficult. Often, the canal is located and the frequency of healing is around 80-89% for cases with no technical failures; however, long-term prognosis may be significantly affected in such cases where the operator is unable to conservatively locate the root canal space due to excessive loss of pericervical dentin (15,16). The American Association of Endodontists has recognized the challenges in treating these cases and categorized the treatment of teeth with PCO as a high difficulty level (17). With an increased risk of perforation, much care should be exercised during access cavity preparation, canal negotiation and instrumentation.

Until recently, endodontic accesses have been performed exclusively by freehand methods. Practitioners continue to utilize various diagnostic tools to locate calcified canals intraoperatively such as the laws of internal anatomy, digital radiography, methylene blue dye and transillumination (18). Magnification (x3 to x20) and intense illumination greatly assist in endodontic procedures. Use of the dental operating microscope (DOM) has greatly enhanced the clinician's capability to adequately and more successfully treat nonsurgical and surgical endodontic cases (19,20).

The development of cone-beam computed tomography (CBCT) imaging has led to great advances in diagnosis and treatment planning and its use for endodontic treatment has increased in recent years. This imaging modality provides 3-dimensional (3-D) scans of the dentition and maxillofacial structure and offers inherent diagnostic value and limited radiation exposure when used properly (21,22). There are numerous applications and advantages to utilizing CBCT imaging in endodontics (21,23). The practitioner may obtain a CBCT preoperatively or intraoperatively to provide 3-D visualization that will aid in location of canal spaces as well as contribute to a more predictable treatment outcome (24). This diagnostic tool has significantly improved the operator's ability to identify canals and anatomical complexities, as well as better manage more challenging cases (25–27).

Although these aids are extremely beneficial in navigation of a calcified canal space, a proper and adequate access cavity may result in excessive loss of dentin tooth structure. Technical complications most commonly encountered when treating these cases include removal of excessive tooth structure, perforation and separation of instruments. In the absence of technical complications, the outcome for root canal treatment of teeth with PCO is similar to that of a tooth without a reduced canal lumen with a necrotic pulp; however, when technical complications are encountered, 50% of these teeth do not heal radiographically (15).

A tooth is increasingly destabilized by any treatment, but most significantly after access preparation and more invasive treatments such as post preparation (28). Substance-saving instrumentation results in only minor destabilization if the root canal geometry is preserved (28). With this in mind, conservative preparation techniques may be desired to minimize the loss of tooth structure, particularly pericervical dentin. The concepts of conservative and ultraconservative "ninja" endodontic cavity preparations have newly emerged and have shown that teeth prepared with these have a higher fracture resistance than those prepared via a conventional endodontic access cavity (29). Although conservative preparations may be ideal and desired, there are cases where these modern approaches for freehand access endodontic cavity preparation are difficult to achieve. Attempts have been made to find a more safe and efficient method for canal location.

The concept of utilizing some form of guidance has been present for quite some time within implant dentistry. Accurate positioning of an implant is crucial to ensure placement at the desired angulation and depth to avoid anatomic and restorative challenges (30). With the introduction and implementation of CBCT within dentistry, treatment planning has been transformed so the ideal implant position may be determined preoperatively. Several techniques have been developed in an attempt to improve the accuracy of implant placement (31–37). These techniques have recently been incorporated in endodontics for microsurgical and nonsurgical accesses, referred to as 'guided endodontics.' There are two types of computer-assisted guidance: static and dynamic (38–41).

Static guidance involves use of a fixed rigid stent with incorporated sleeves that guides the bur into the calcified root canal. A minimally invasive access cavity is planned virtually using computer-aided design/computer-aided manufacturing (CAD/CAM), based on a preoperative CBCT scan and a 3-D surface scan. This is translated into a printed template with incorporated sleeves that guide the bur directly to the orifice of the root canal system to reduce the margin of error. It aims to preserve tooth structure and avoid perforations. The pre-planned position of the endodontic access is dependent on the stent without the ability to change the access template position. This system demonstrates a high level of accuracy with little deviation of executed access preparation form the pre-planned access (37,42,43). There are also several drawbacks to this technique such as additional treatment time, need for template fabrication, difficulty of use in posterior teeth, lack of real-time visualization and a predetermined drill position that cannot be changed during the procedure (34).

An alternative method referred to as 'dynamic navigation,' incorporates motion-tracking optical cameras and images of the position of the virtually planned implant correlated to reference points and provides real-time dynamic and visual feedback to guide the surgical implant drills. The CBCT scan is uploaded to the dynamic guidance system software and utilized for presurgical planning and visualization. Thereafter, the precise location of the access preparation is positioned within the software, reference points are created and calibrated and the plan is transferred to the live clinical situation. With successful calibration, precise position of the handpiece can be tracked (35,36,41). This provides the surgeon with better visualization during the implant preparation and the position and angulation of the drill can be adjusted at any time during the surgery. There are several dynamic guidance systems utilized for implant placement: RoboDent (RoboDent), X-Guide (X-Nav Technologies), Image Guided Implantology (Image Navigation) and Navident (ClaroNav). These systems reduce errors and are superior in accuracy to manual (freehand) implant placement (31,35,36). They are comparable or superior in accuracy to other computer-assisted surgical techniques such as static guides (36). The main advantage of dynamic navigation technology is the flexibility that allows the operator to adjust the plan at the treatment appointment. The surgical plan or access preparation may be modified as indicated by the clinical situation by adjusting any of the following parameters chair-side: positioning, angulation, depth, as well as diameter of the access that corresponds to the type of bur used.

'Guided endodontics' has focused on the use of static guides until recently. Dynamic navigation technology has the potential to be applied in endodontics for access cavity preparation and canal location, particularly in cases with severe canal calcification. There is only one study to date with data to support that computer-aided dynamic procedures allow more accurate and safe endodontic access preparations when compared to the conventional freehand technique (44). Although the findings were favorable regarding accuracy of static and dynamic guidance in comparison to the manual (freehand) group, the study did not provide further analyses regarding the amount of tooth structure removed during endodontic access preparation nor reported the amount of time that was taken in performing these accesses.

Most studies utilizing dynamic navigation for implant placement and endodontic access to date have reported using an artificial radiographic marker, also known as "fiducial." (35,36,44). Previously, the patient would have to be CBCT-scanned with the thermoplastic splint which would later be identified in the CBCT images by the navigation system's software in order to enable registration (34). Recently, a technology referred to as trace registration was developed to allow dynamic navigation of implant placement or endodontic access without the need for a thermoplastic stent. The trace registration method eliminates the need for the thermoplastic splint to be present in the image. The software will instead recognize natural high-contrast surfaces, such as tooth crowns or abutments already present in the image. The main advantages to this innovative trace registration method include: eliminating the need to design and fabricate a stent or guide in advance, eliminating risk for inaccuracy due to improper seating of the stent during the scan or procedure and that an existing CBCT scan may be used.

This *in vitro* study was designed to evaluate and compare dentin preserving capacity of a dynamic 3-dimensional navigation system (utilizing trace registration technology) to a freehand method in locating calcified canals in single-rooted maxillary and mandibular prefabricated endodontic 3-D printed teeth using an *ex vivo* model.

The main objectives of this study were to compare each of the following in both experimental groups:

1). Evaluate the ability to successfully locate the canal space.

2). Compare the frequency of unsuccessful attempts in canal identification.

3). Compare the frequency of perforations.

4). Compare amount of tooth structure removed via volumetric analysis and operator improvement over time.

5). Compare the time necessary for canal location and negotiation and operator improvement over time.

Methods

Forty identical maxillary (n = 20) and mandibular (n = 20) single-rooted anterior 3-D printed teeth (TrueTooth, DELabs, Santa Barbara, CA, USA) were utilized in this study. Each tooth simulated a canal that had undergone pulp canal obliteration. The tooth model contained a canal space that was diminished in size and was apical to the level of the cementum-enamel junction (CEJ) landmark. *Figure 1a* and *b* exhibit the unmounted maxillary (#9) and mandibular (#25) tooth models from mesial, facial, lingual and distal views. *Figure 2a* and *b* exhibit digital 3-D renderings of the maxillary (#9) and mandibular (#25) tooth models from facial and mesial views. The red color represents the pulp canal space. The distance from the incisal edge to the canal space in the maxillary anterior tooth (#9) measured approximately 16.0 mm and for the mandibular anterior tooth (#25) measured approximately 13.0 mm. The teeth were an opaque white color and inside the canal space was a red wax material. Both sets of teeth were further divided into two different treatment groups (freehand access (F) and dynamically navigated access (N)) and four different subgroups (maxillary teeth treated via freehand method (FU), maxillary teeth treated via dynamic navigation method (NU), mandibular teeth treated via freehand method (FL), mandibular teeth treated via dynamic navigation method (NL)). The treatment teeth were individually mounted according to their anatomic position in a maxillary or mandibular ModuPRO Endo jaw model (Acadental, Overland Park, KS, USA) to simulate a partially dentate maxilla or mandible (*Figure 3*). Additionally, extracted human teeth were mounted in empty slots within the jaw models that would later be utilized for the trace registration calibration. A small amount of rope wax was placed onto the apex of each treatment tooth prior to mounting. After setting of the putty mounting material (Splash! Putty, DenMat, Lompoc, CA, USA), the teeth were retrieved and superglued (Scotch, 3M, St. Paul, MN, USA) into place. The mounted anterior treatment teeth were randomly assigned into four experimental groups:

1) Freehand (F) method - Maxillary anterior tooth (#9) (FU) (n = 10),

2) Dynamic 3-D Navigation System (N) - Maxillary anterior tooth (#9) (NU) (n = 10),

3) Freehand (F) method - Mandibular anterior tooth (#25) (FL) (n = 10),

4) Dynamic 3-D Navigation System (N) - Mandibular anterior tooth (#25) (NL) (n=10).

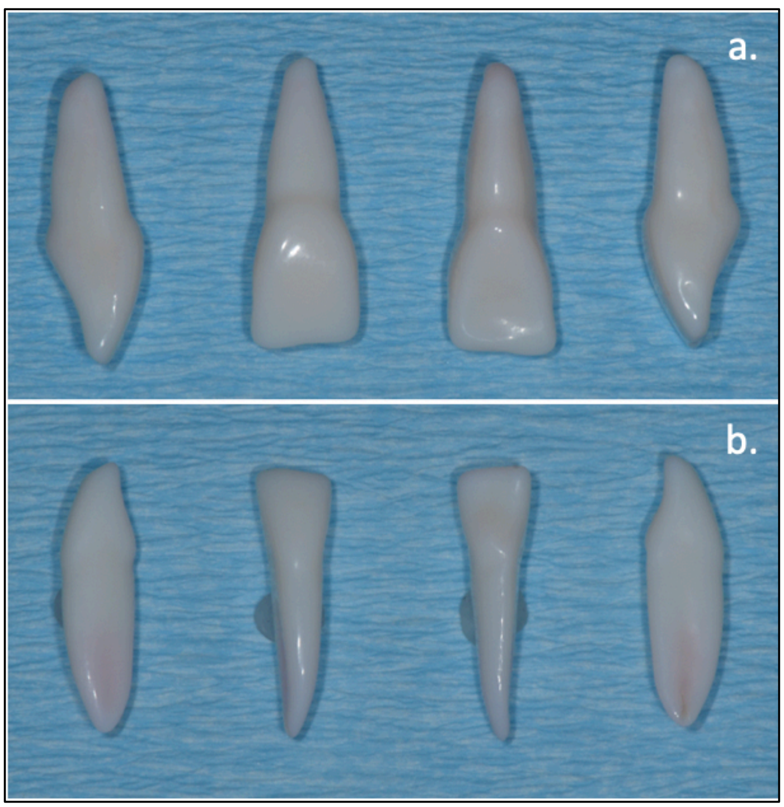

Figure 1: Unmounted Maxillary (a) and Mandibular (b) Tooth Models

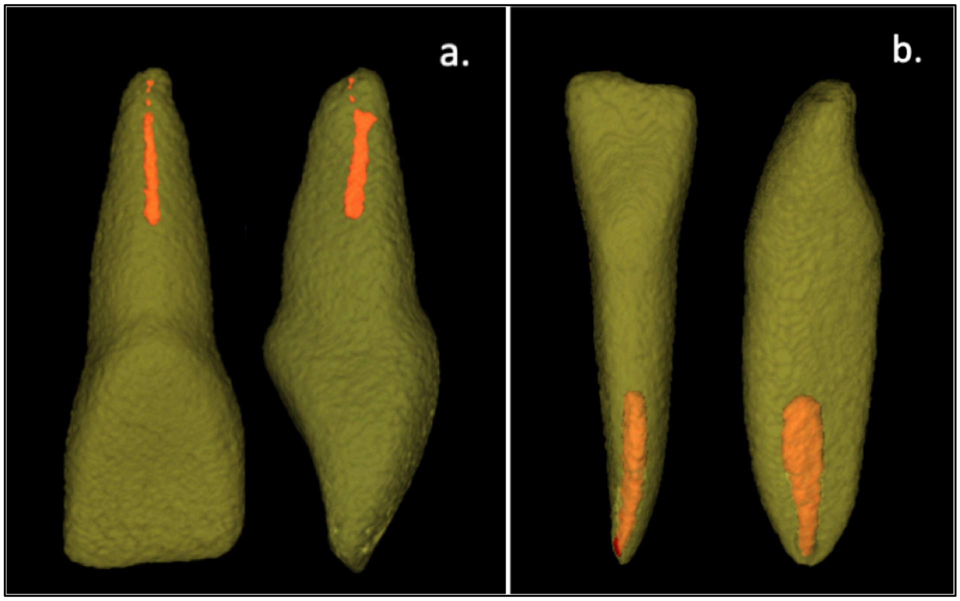

Figure 2: Digital 3-D Renderings of Maxillary (a) and Mandibular (b) Tooth Models

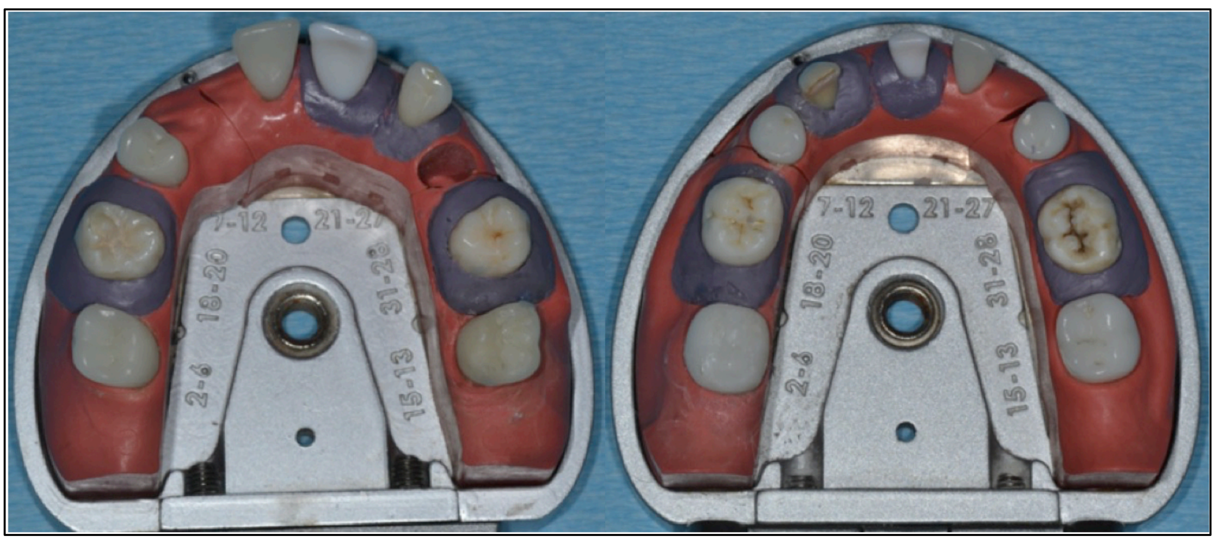

Figure 3: Maxillary and Mandibular Jaw Models including Mounted Treatment Tooth and Extracted Teeth

Pre-operative full arch model CBCT scans were obtained for each dynamic navigation treatment case using a CBCT unit (CareStream Kodak 8100 3-D Cone Beam, Carestream Dental, Atlanta, GA) with the following parameters: 60 kilovolt peak, 2.0 milliamperes, 15.0 s, 150 µm voxel size and a field of view (FOV) of 8 cm x 5 cm. A full arch scan is extremely useful in these cases as there will be more teeth and reference points within the scan to select for the trace registration process described below. Pre-operative limited FOV CBCT scans were obtained for each freehand treatment case with the following parameters: 60 kilovolt peak, 2.0 milliamperes, 15.0 s, 150 μm voxel size and a FOV of 4 cm x 4 cm. A limited FOV was obtained for freehand treatment cases as a full arch scan was not necessary for visualization of the treatment tooth. For the maxillary treatment teeth, only the maxillary arch of the jaw model was scanned and only a scan of the mandibular arch was obtained for the mandibular treatment teeth. Items from the 3-D object acquisition accessories kit were utilized and placed onto the 3-D bite block support attachment to position and stabilize the dental arch for scanning purposes (*Figure 4*).

Figure 4: Pre-operative CBCT Acquisition of Jaw Model(s)

The treatment order of teeth was predetermined via block randomization (see *Table 1*). A maximum of five teeth were accessed in one treatment session. All teeth were accessed over a period of four months with at least one week between each treatment session to decrease the operator's familiarity of techniques employed for each method during a treatment session. All teeth were treated under rubber dam isolation. Access, canal identification and verification was completed by the primary investigator, a second-year endodontic resident.

Table 1: Treatment Order Based on Block Randomization

Treatment	***Block***	***Method/Jaw***		***Treatment***	***Block***	***Method/Jaw***
1	1	FU-1		**21**	3	NL-6
2	1	FL-1		**22**	3	FU-6
3	1	NL-1		**23**	3	NU-5
4	1	NU-1		**24**	3	NU-6
5	1	FU-2		**25**	4	FL-7
6	1	NL-2		**26**	4	NU-7
7	1	FL-2		**27**	4	NU-8
8	1	NU-2		**28**	4	FU-7
9	2	NL-3		**29**	4	NL-7
10	2	NU-3		**30**	4	FU-8
11	2	NU-4		**31**	4	FL-8
12	2	FL-3		**32**	4	NL-8
13	2	FL-4		**33**	5	NU-9
14	2	NL-4		**34**	5	FL-9
15	2	FU-3		**35**	5	NL-9
16	2	FU-4		**36**	5	FU-9
17	3	FL-5		**37**	5	NL-10
18	3	FL-6		**38**	5	FL-10
19	3	FU-5		**39**	5	FU-10
20	3	NL-5		**40**	5	NU-10

Freehand Access Protocol:

The following burs were available for use with high speed handpiece for freehand access procedures: surgical length #2 round bur (COLTENE, Altstätten, Switzerland), 859 FGSL bur (Komet USA, Rock Hill, SC, USA) and an EndoZ bur (Dentsply Sirona, York, PA, USA). The burs were cleaned regularly during preparation using a sterile gauze. Distilled water was placed within an irrigation syringe with a 27-gauge needle and used when the operator desired to eliminate debris from prepared access. Preoperative limited FOV CBCTs were reviewed and access cavity preparations were made utilizing a dental operating microscope (Global Surgical Corporation, St. Louis, MO, USA). The limited FOV CBCT scan was available to view during the procedure for aid in assessing angulation and measurements. No periapical images were obtained intraoperatively.

Dynamic Navigation Access Protocol:

In the dynamic navigation group, access cavities were made under full guidance of the dynamic navigation system (Navident, ClaroNav, Toronto, Canada) according to manufacturing instructions. The data set from the CBCT was imported to the treatment planning software on the mounted laptop computer on the mobile unit. The software facilitated planning of the access cavity design and path of drilling needed to locate the canal space based on the CBCT data sets. The process was similar to planning for an implant placement. However, for endodontic purposes, a 1.0 mm diameter drill template served as the guiding path for the bur during the procedure. The operator adjusted the yellow ‘implant’ image to be used for the guidance (diameter, length, position and direction). Axial, coronal and sagittal views were aligned to set up the correct path for the bur to follow. The access was planned from approximately the incisal edge of the corresponding maxillary or mandibular anterior tooth to the canal space to account for straight-line access. The same access cavity planning process was completed for all dynamic navigation treatment teeth (n = 20) (*Figure 5*).

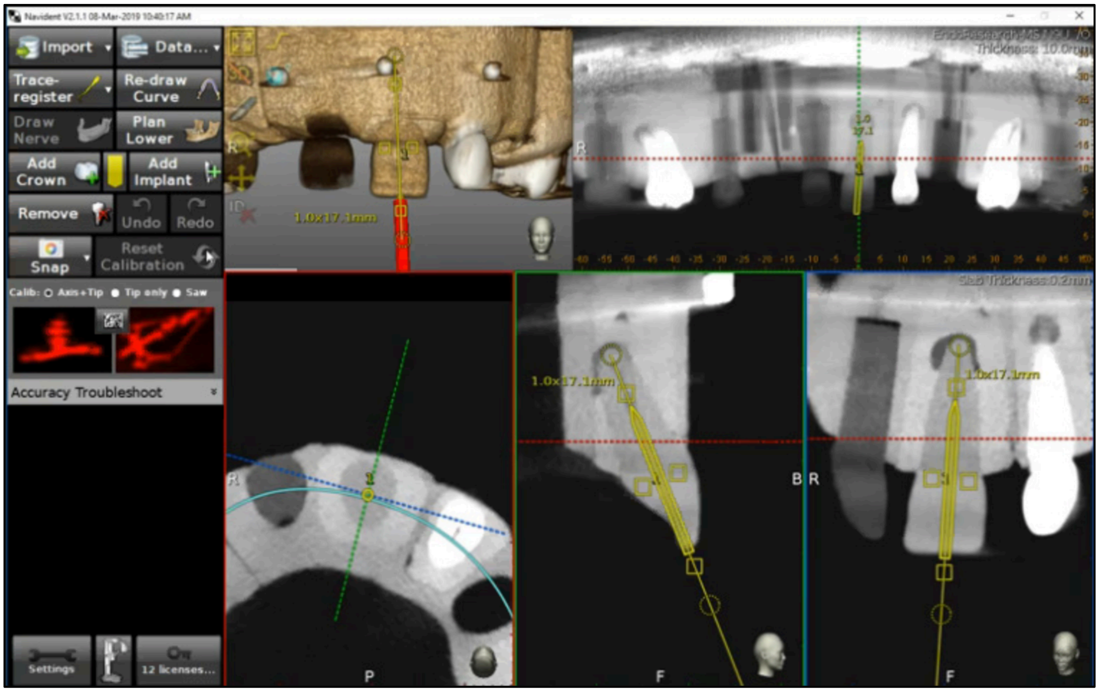

Figure 5: Screenshot of Planned Endodontic Access within Dynamic Navigation Software
The planned endodontic access is represented by the yellow color and is exhibited via axial, sagittal and coronal views.

The dynamic navigation treatment group required additional set-up to allow for the real-time navigation procedure. A black-and-white tracking tag ("jaw tag") was attached with a resin material (CompCore AF SyringeMix Stack, Premier Dental, Plymouth Meeting, PA) to the dental arch containing the treatment tooth to enable the dynamic navigation system to track the position of the jaw (*Figure 6*). The CBCT scan was then mapped to the actual jaw by trace registration. This utilized the existing, radiographically distinct anatomical structures of the jaw, such as teeth. The tracer tool (*Figure 7a*) was calibrated using the calibrator tool (*Figure 7b*). Three reference points on teeth surfaces were marked on the CBCT scan (*Figure 7c*). These three surfaces were then traced with the tracer tool that was also tracked by the dynamic navigation system optical positioning sensor (*Figure 7d*). The system continuously recorded points on the traced teeth and this was matched with the CBCT data to register it with the model jaw. Successful trace registration was confirmed visually by placing the tracer tip onto arbitrary surfaces of the extracted teeth mounted in the dental arch as well as the treatment tooth to ensure the positioning corresponded to what was seen real-time within the software on the computer screen. Following this step, a black-and-white tracking tag ("handpiece tag") was placed onto the high-speed handpiece using the rubber sleeve provided (*Figure 8a*). The handpiece was then tracked by the system and the axis of the handpiece and the bur were both calibrated using the calibrator tool (Figure *8b* and *c*). An accuracy check was completed by placing the tip of the bur on arbitrary surfaces of the extracted teeth mounted in the dental arch as well as the treatment tooth to ensure the positioning and angulation corresponded to what was seen real-time within the software on the computer screen. Once this was confirmed, the rubber dam was placed onto the treatment tooth. The operator performed each endodontic access cavity by viewing the target on the bottom left of the computer screen which displayed active dynamic navigation relating to position, angulation and depth (*Figure 9* and *Figure 10*). If at any point during a treatment the calibration was in question, the operator would recalibrate and confirm with an accuracy check. For dynamic navigation access procedures, only the 859 FGSL bur was used.

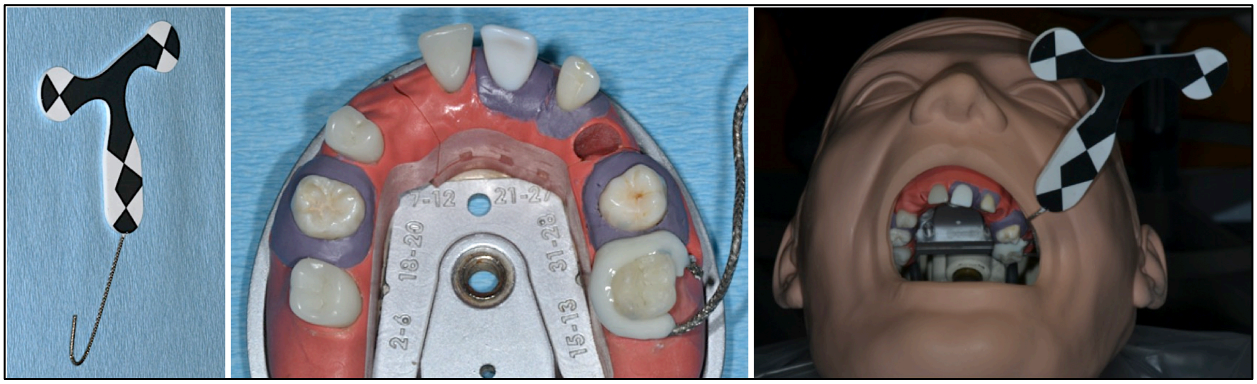

__Figure 6: Fixation of Jaw Tag to Treatment Jaw__

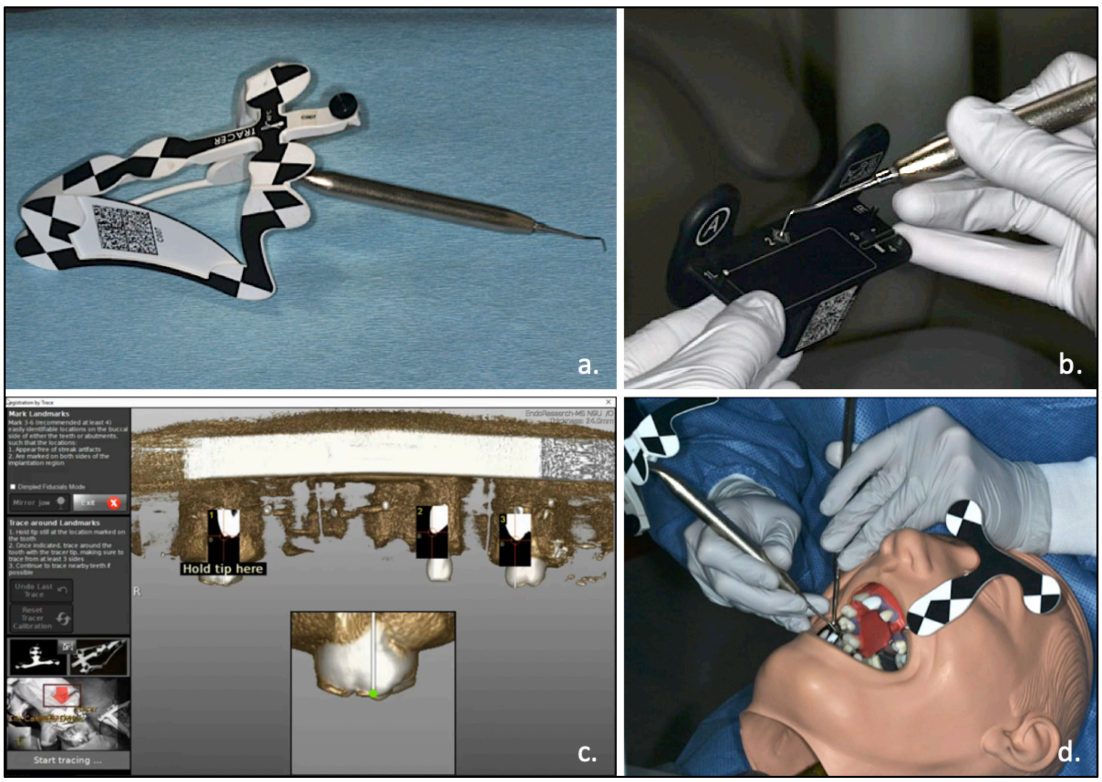

__Figure 7: Trace Registration Calibration Process__

Tracer (a), Calibration of Tracer tip (b), Selection of Reference Points on CBCT Rendering (c), Executing Trace Registration Process by placing Tracer Tip over Clinical Reference Point marked on CBCT Rendering (d)

Figure 8: Calibration Process for Handpiece Axis and Bur
Handpiece with Tag Attached (a), Calibration of Handpiece Axis (b), Calibration of Bur (c)

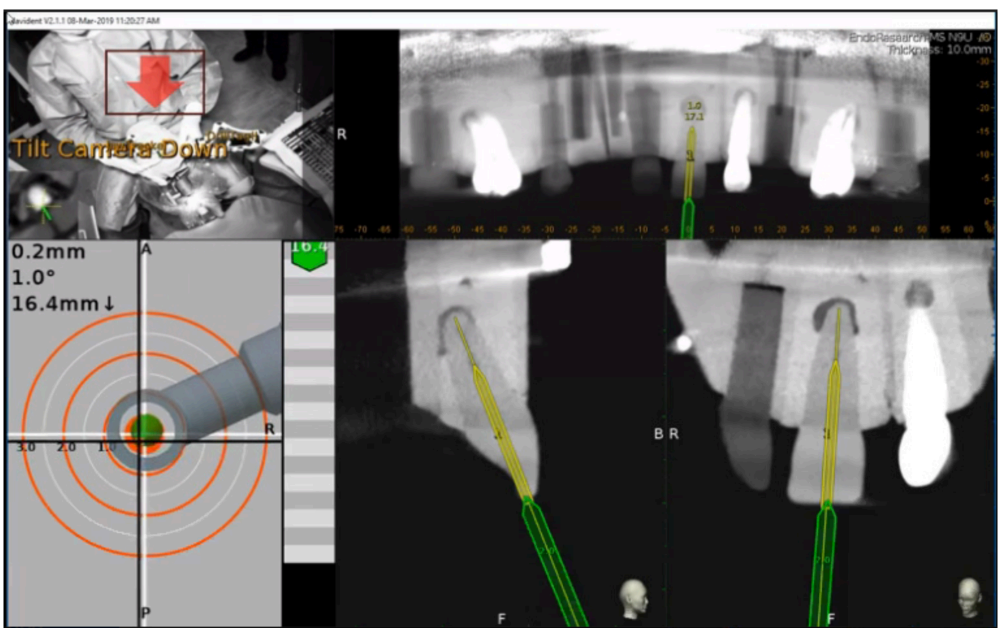

Figure 9: Screenshot of Endodontic Access Procedure Utilizing Dynamic Navigation System Exhibiting Realtime Feedback
The bur is indicated by the green color. The software contains color-coded feedback that will alert the operator if the executed access preparation falls outside an acceptable range of accuracy.

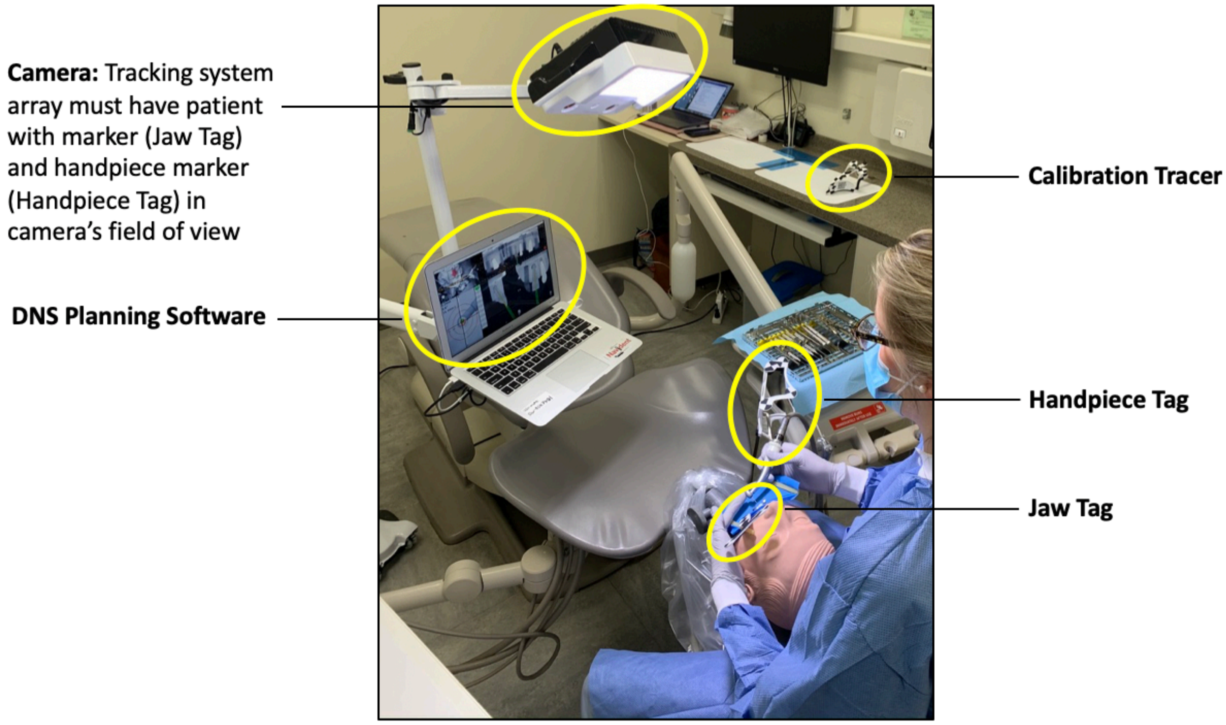

Figure 10: Dynamic Navigation System Clinical Setup

The duration of each freehand and dynamic navigation access cavity preparation treatment was recorded with a stopwatch (Apple Inc., Cupertino, CA, USA) from the time the operator began access preparation of tooth structure to the point of successful canal negotiation. In the freehand group, the access cavity preparation was completed when the canal was located or when the operator suspected a perforation or deemed the tooth non-restorable. In the dynamic navigation group, the access cavity process was completed when the bur reached the end of the planned drill path. All burs used for access preparation were replaced and not reused for the next tooth.

Success in canal location was confirmed by placing a #15 K-file (Dentsply Sirona, York, PA, USA) within the access/canal to an estimated working length. Red wax was also visualized once the canal space was located when using the dental microscope. The mounted treatment tooth was removed from the typodont and periapical radiographs were obtained from facial and mesial views to radiographically evaluate for perforations (*Figure 11a* and *b*) and to evaluate successful location of the canal space with the #15 K-file (*Figure 11c* and *d*). Treatment teeth were removed from the mounting material to visually assess for perforations. The number of perforations or unsuccessful attempts for canal location in both groups was recorded.

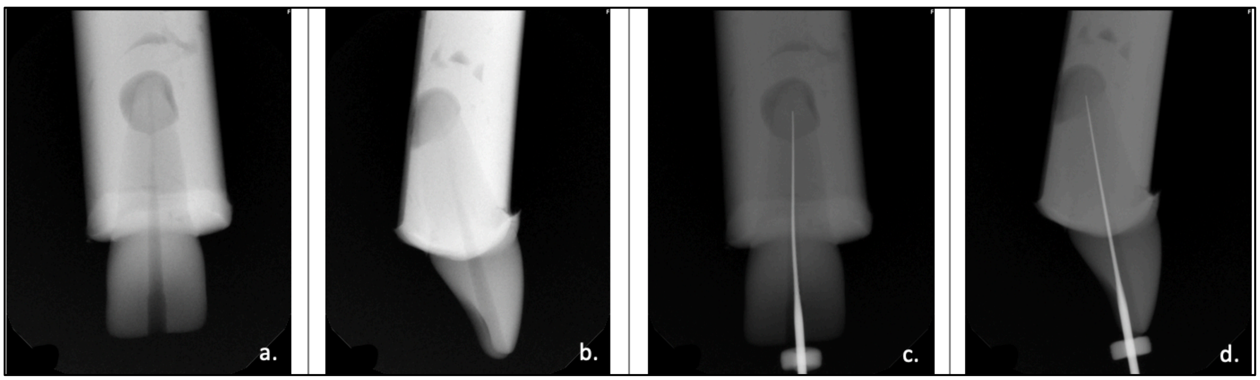

Figure 11: Postoperative Periapical Images from Facial (a, c) and Mesial (b, d) Views With (c,d) and Without (a,b) a #15 K-file Confirming Location of Canal Space

Following access preparation in both treatment groups, a postoperative CBCT scan was obtained once each individual tooth was removed from its mounting material with the following parameters: 60 kilovolt peak, 2.0 milliamperes, 75 μm voxel size and a FOV of 4 cm x 4 cm. The postoperative scans were submitted to a board-certified Oral and Maxillofacial Radiologist for volumetric analysis of the tooth structure removed. CBCT scans obtained for both pre-operative tooth models were submitted to serve as a baseline prior to any tooth preparation. The Radiologist was blinded to the treatment modality used for each tooth.

All scans were analyzed with the ITK/SNAP DICOM viewer (http://www.itksnap.org/download/snap/), an open source medical image computing platform for biomedical research. Once the postoperative CBCT scan was uploaded into the ITK/SNAP DICOM viewer software (*Figure 12*), a semi-automatic segmentation tool was used to segment the tooth structure as a foreground while lower thresholding values were used to exclude the prepared canal in the background (*Figure 13*). Active contour evolution was automatically done by ITK SNP after placing “active bubbles” on the tooth surface in coronal and sagittal planes (*Figure 14*). The “active bubbles” then evolved (*Figure 15*) and once the evolution was completed (*Figure 16*), the software then automatically analyzed the tooth volume and provided a 3-D rendering of the prepared tooth (*Figure 17*).

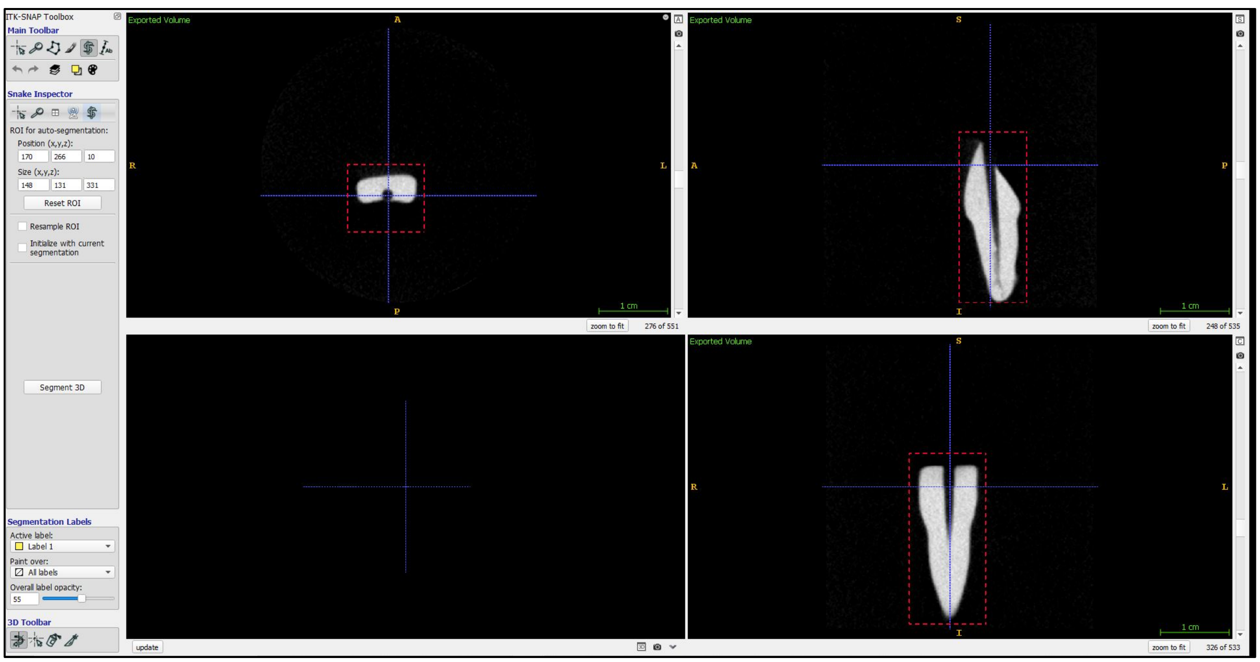

Figure 12: Screenshot of CBCT Scan Uploaded to ITK/SNAP DICOM Viewer Software

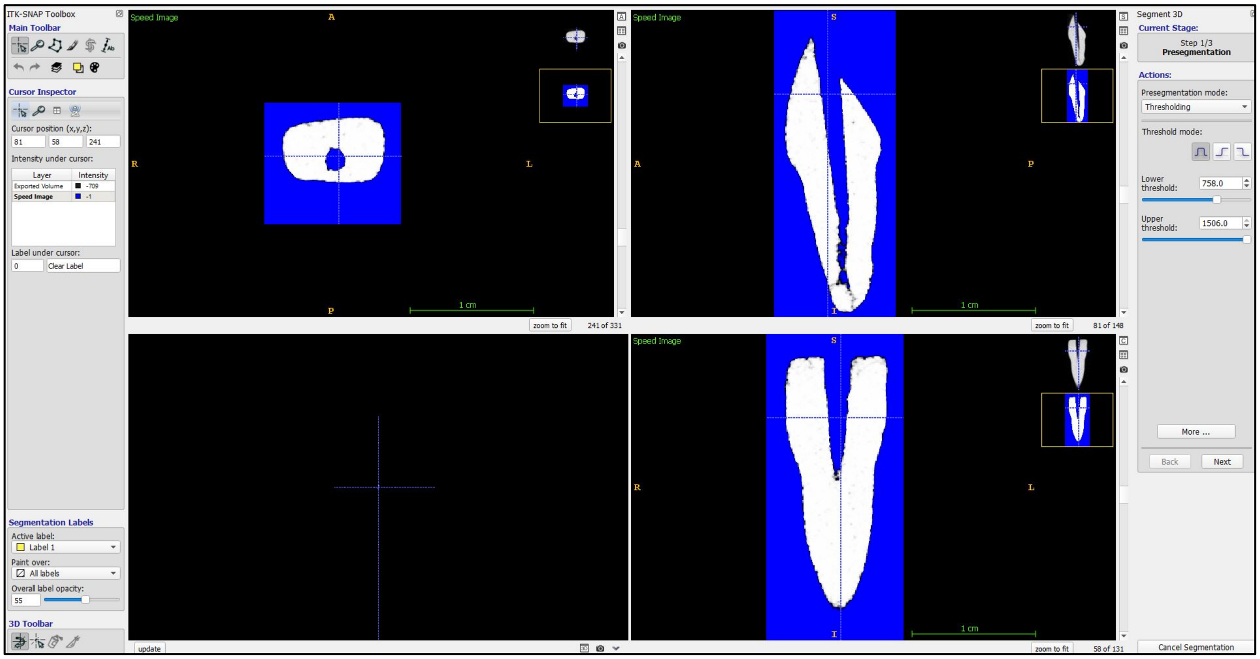

Figure 13: Screenshot of Segmented Tooth Structure and Thresholding Values

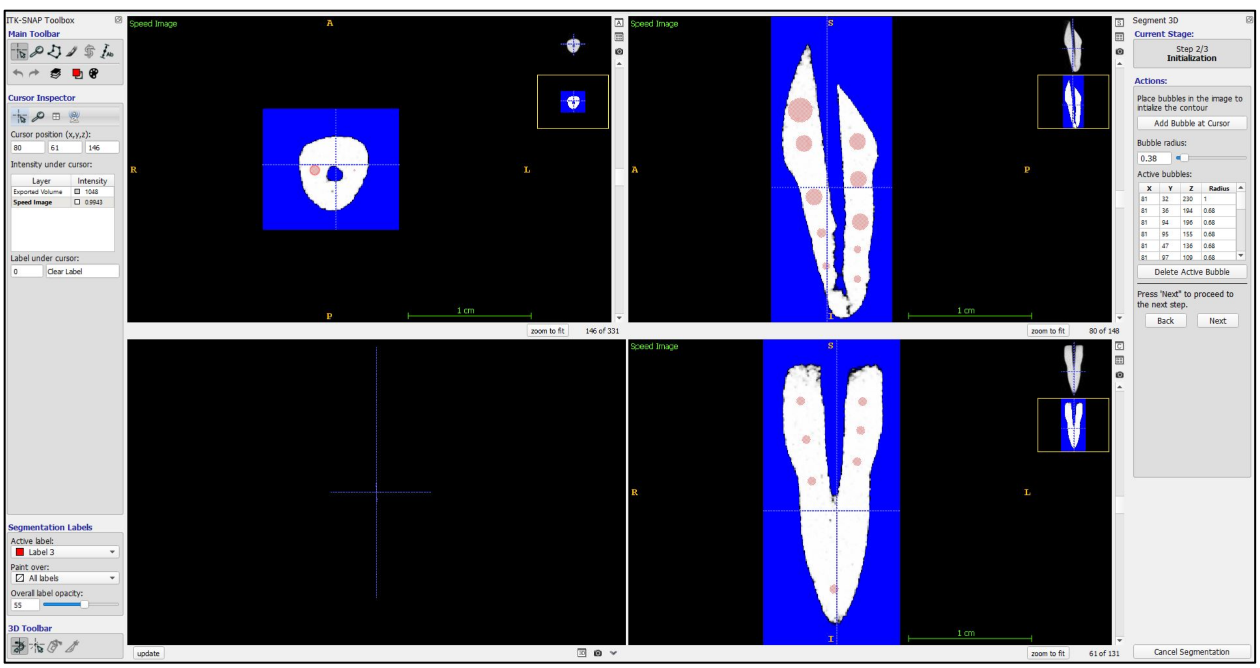

Figure 14: Screenshot of Placement of "Active Bubbles" onto Tooth Structure

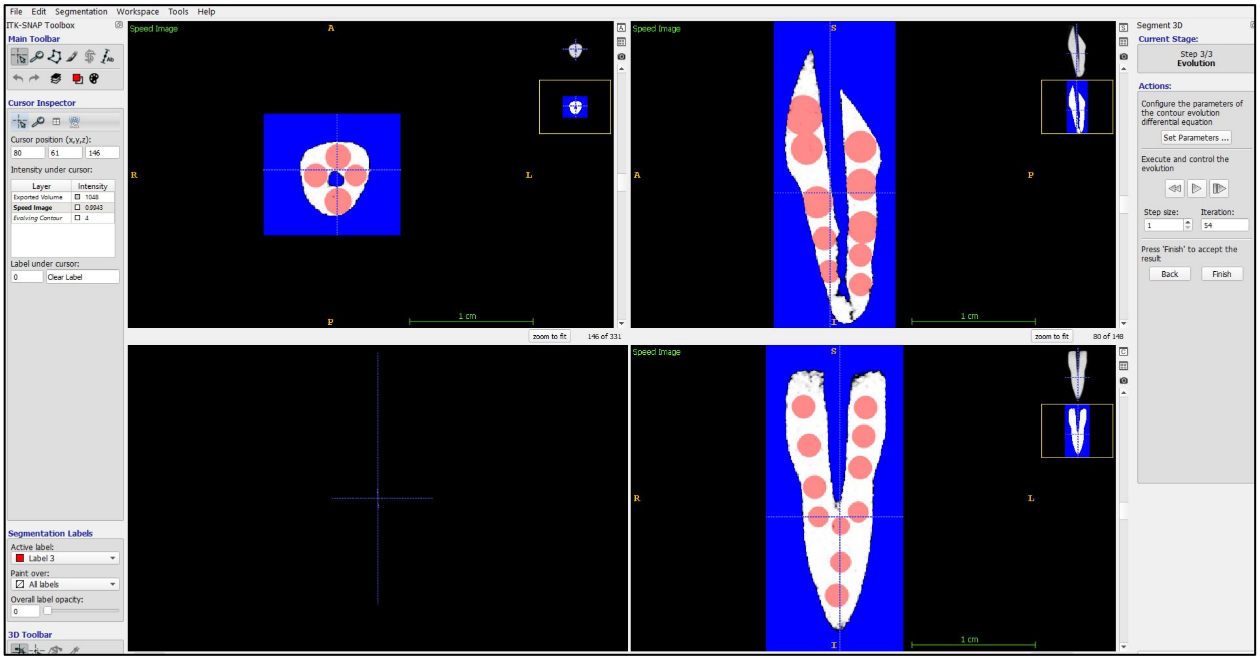

Figure 15: Screenshot of Active Contour Evolution

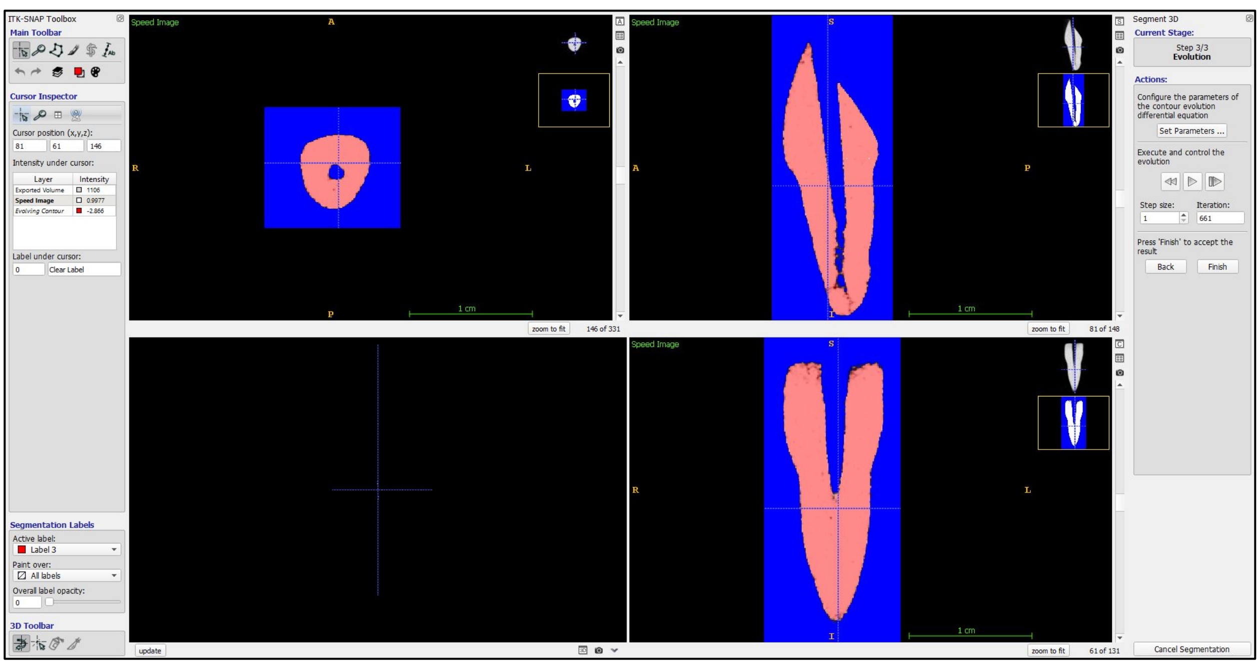

Figure 16: Screenshot of Completed Evolution

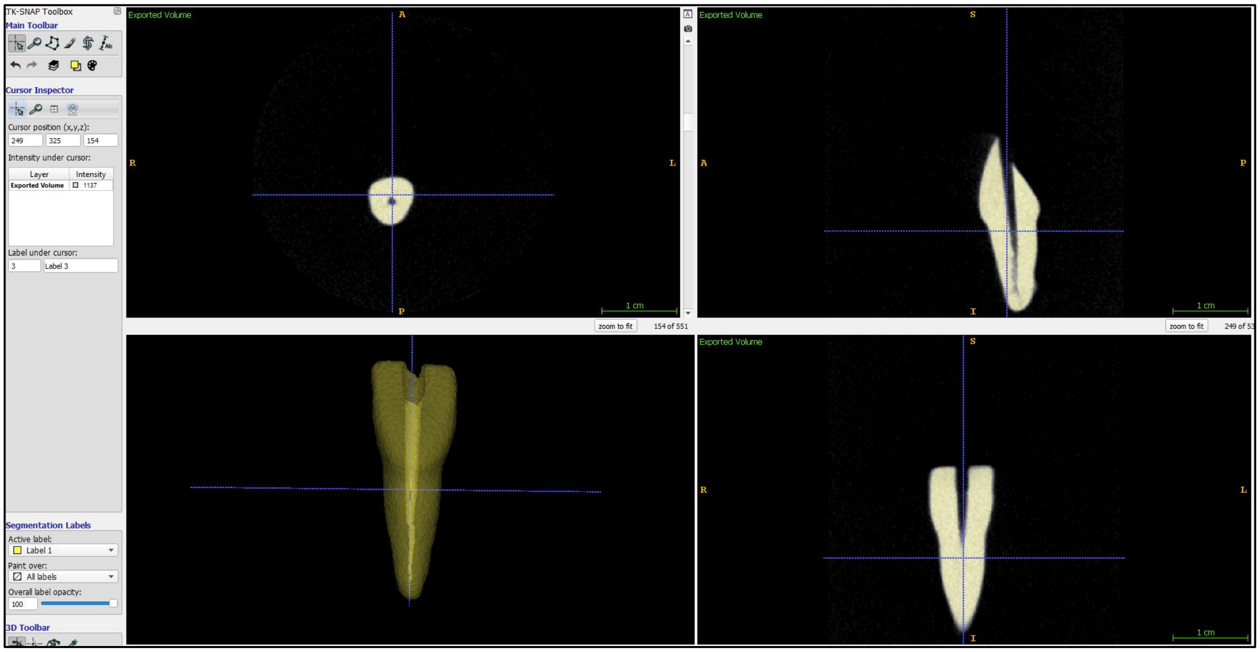

Figure 17: Screenshot of 3-D Rendering of Prepared Tooth

Successful location of the canal and perforation rate were compared between the two methods using Fisher's Exact test. The associations between jaw, method (freehand or dynamic navigation), the attempt number and the outcome variables (tooth structure removed and operating time) were determined using ANOVA models with Tukey's adjusted post hoc pairwise comparisons. Significance level was set at 0.05 and SAS EG v.6.1 was used for all analyses.

Results

1). Ability to successfully locate the canal space:

A total of twenty attempts were completed with each method (freehand and dynamic navigation) with ten attempts on each of the two jaws. The canal space was located in 20/20 teeth treated via freehand treatment method and 18/20 teeth treated via dynamic navigation treatment method.

2). Frequency of unsuccessful attempts in canal identification:

There were two instances of unsuccessful canal location and both attempts were within dynamic navigation treatment groups (one mandibular tooth (NL-7), one maxillary tooth (NU-10)). The method of treatment relating to unsuccessful attempts was not statistically significant (F-0% vs N-10%, p-value=0.4872).

3). Frequency of perforations:

There were three instances of access perforations. Two access perforations occurred within the freehand treatment groups (one maxillary tooth (FU-5), one mandibular tooth (FL-10)) and one within a dynamic navigation treatment group (mandibular tooth (NL-7)). The method of treatment relating to access perforations was not statistically significant (F-10% vs N-5%, p-value=1.00).

4). Amount of tooth structure removed and operator improvement over time:

There were significant differences in the mean tooth structure removed based on the treatment group (p-value<0.001). The difference between treatment methods on the mandibular teeth (FL and NL) was negligible (19.1 mm^3, 19.0 mm^3, respectively), with an average difference of 0.14 mm^3 (adjusted p-value=1.00). These two treatment groups also had the lowest overall amount removed. Attempts with the dynamic navigation treatment method for the maxillary teeth (NU) removed an average of 35.5 mm^3 of tooth structure, which was significantly higher than the amount removed via dynamic navigation treatment method for the mandibular teeth (adjusted p-value=0.0026). The average amount of tooth structure removed for the freehand treatment method in the maxillary teeth (FU) was 62.2 mm^3, which was significantly higher than any other treatment group (p-value<0.0001). The average amount of tooth structure removed in the FU treatment group was on average 26.7 mm^3 more than the NU treatment group (p-value<0.0001, 95% CI: 17.99-35.42). The amount of tooth structure removed did not significantly decrease or improve from attempt 1 to attempt 10 when data from all treatment groups was combined (p-value=0.1122) nor was there a difference noted between each individual treatment group (p-value=0.3318). The analysis was repeated after removing the cases where the canal was not located, but the results did not change in any statistically or clinically meaningful manner. Results are given in *Table 2* and *Figure 18*.

Table 2: Average Tooth Structure Removed (mm3) by Jaw and Method

Method/Jaw	***Mean Structure Removed (mm^3)***	***Standard Error***	
Dynamic Navigation Mandible (NL)	19.0	3.04	a
Freehand Mandible (FL)	19.1	3.04	a
Dynamic Navigation Maxilla (NU)	35.5	3.04	b
Freehand Maxilla (FU)	62.2	3.04	c

*Levels with the same letter were not significantly different

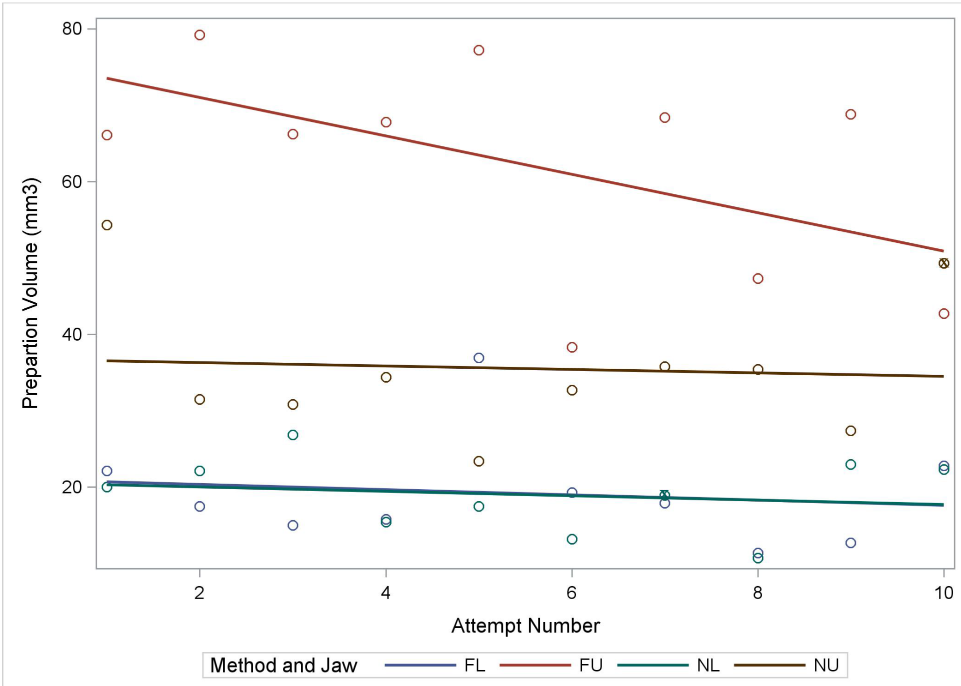

Figure 18: Tooth Structure Removed (mm³) by Attempt Number and Method/Jaw Combination

This displays the preparation volumes from all access attempts (1-10). Each colored miniature circle represents the preparation volume corresponding to the accessed/treated tooth and each colored line represents the average tooth structure removed (mm³) throughout multiple attempts within each treatment group (FU, FL, NU, NL). An 'x' was placed over each attempt (represented by a miniature circle) resulting in unsuccessful location of the canal space. Each data set shows a trend of improvement (gradually conserving more tooth structure) over time with each subsequent attempt

<u>5). Time necessary for canal location and negotiation and operator improvement over time:</u>

Time to complete the procedure was significantly related to the method, jaw and attempt number. The average treatment times are displayed in *Table 3*. The average treatment time across all attempts was significantly different for the treatment method and jaw combinations (p-value<0.0001). After adjusting for multiple comparisons, the freehand treatment method attempts in maxillary teeth (FU) were significantly longer than any of the other three treatment groups (p-value≤0.0001 for all comparisons). When comparing by the attempt number, the freehand treatment method attempts in maxillary teeth (FU) were significantly longer than the other three treatment groups until the ninth attempt at which point the FU group was not significantly different from the FL group (adjusted p-value=0.2768) or the NU group (adjusted p-value=0.1087). By the tenth attempt, the FU group was not significantly longer than the NL (adjusted p-value=0.1778). The differences between the remaining three groups were not statistically significant at any of the attempt numbers (p-value>0.2).

Table 3:Average Treatment Time (minutes) by Jaw and Method

Method/Jaw	***Average Time (mins)***
Freehand Maxilla (FU)	10:59
Dynamic Navigation Maxilla (NU)	03:49
Freehand Mandible (FL)	04:11
Dynamic Navigation Mandible (NL)	02:47

Although the effect of the attempt number was not significantly dependent on the method and jaw (p-value=0.1071), the freehand treatment method attempts in the maxillary teeth (FU) exhibited a significant decrease in time for each subsequent attempt (average decrease in time: 52.43 seconds (SE=23.58), p-value=0.0334). For all the other jaw-method combinations, the change in time across attempts was not significantly different from 0 (p-value>0.6). The analysis was repeated after removing the cases where the canal was not located, but the results did not change in any statistically or clinically meaningful manner. Complete results are given in *Table 4* and *Figure 19*.

Table 4: Estimated Time (seconds) and Standard Error (seconds) by Attempt, Method and Jaw

Attempt	*FL*	*NL*		*FU*	*NU*	
1	327.1, 89.01	151.4, 89.01		870.8, 89.01	200.8, 89.01	*
2	310.1, 75.49	141.6, 75.49		810.3, 75.49	192.8, 75.49	*
3	293.2, 63.49	131.9, 63.49		749.9, 63.49	184.8, 63.49	*
4	276.2, 54.03	122.1, 54.03		689.4, 54.03	176.8, 54.03	*
5	259.3, 48.61	112.4, 48.61		629.0, 48.61	168.8, 48.61	*
6	242.3, 48.61	102.6, 48.61		568.6, 48.61	160.7, 48.61	*
7	225.4, 54.03	92.8, 54.03		508.1, 54.03	152.7, 54.03	*
8	208.4, 63.49	83.1, 63.49		447.7, 63.49	144.7, 63.49	*
9	191.5, 75.49	73.3, 75.49		387.2, 75.49	136.7, 75.49	
10	174.5, 89.01	63.6, 89.01		326.8, 89.01	128.7, 89.01	

(*) Indicates significant difference between Freehand (F) and Dynamic Navigation (N) within jaw

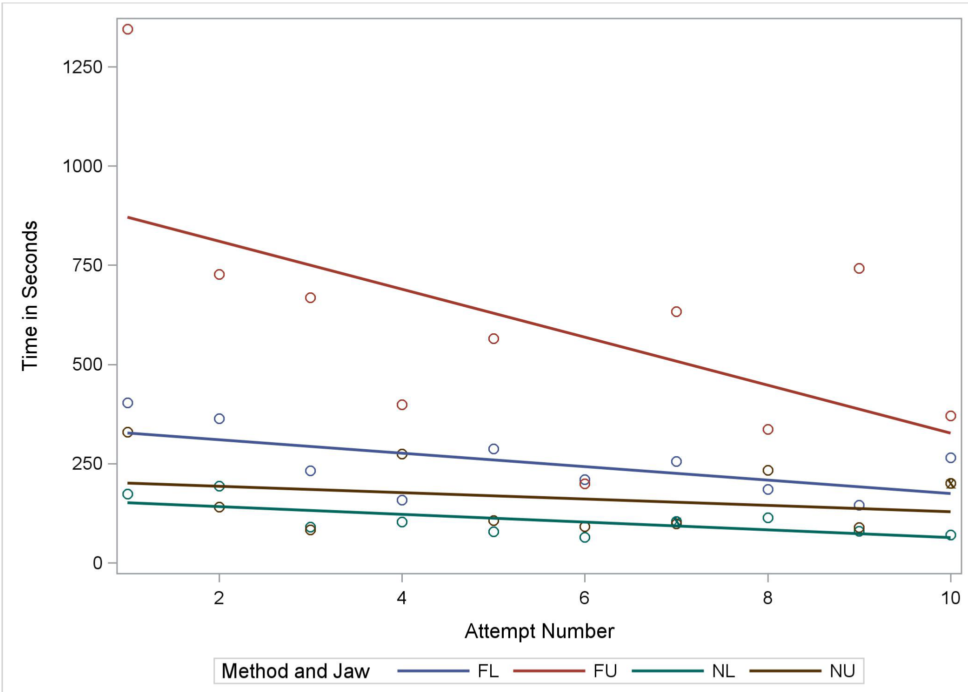

Figure 19: Operation Time (seconds) by Attempt Number and Jaw-Method Combination

This displays the operation time (seconds) from all access attempts (1-10). Each colored miniature circle represents the operation time corresponding to the accessed/treated tooth and each colored line represents the average operation time throughout multiple attempts within each treatment group (FU, FL, NU, NL). An 'x' was placed over each attempt (represented by a miniature circle) resulting in unsuccessful location of the canal space. The differences in treatment time were most significant when comparing the maxillary accessed teeth within the NU and FU treatment groups. There was no significant difference in operation time between the NU, FL and NL groups. Each data set shows a trend of improvement (gradually decreasing operation time) over time with each subsequent attempt.

Discussion

The concept of guidance in dentistry was originally incorporated into the field of dental implant surgery. Computer-aided static navigation techniques with fixed rigid stents were developed in order to aid in planning and accuracy of implant placement (32,33,37). This technique has been applied in endodontics to improve the conservation of tooth structure when performing an endodontic access in more clinically complex cases, such as PCO (38,40,42,43). The static guidance technique has proven to allow for an accurate endodontic access cavity preparation to the apical third of the root. One study identified the deviations among planned and prepared access preparations were minimal with means ranging from 0.16 to 0.21 mm at the base of the bur and 0.17 to 0.47 mm at the tip of the bur with a mean angle deviation of 1.81° (42). These deviations have been attributed to the loose fit between the drill and the guide sleeve which is needed to avoid heat development during access preparation (42). Computer-aided static navigation offers favorable and predictable results in endodontic access preparation in calcified teeth; however, this technique is not invariably successful (40). The main limitations to this guided approach include the fabrication time, use of a slow-speed drill, difficulty of use in posterior regions and lack of ability to change the treatment plan chairside if any complications arise (34). These limitations have promoted the potential application of computer-aided dynamic navigation technology for endodontic access to allow the operator real-time guidance feedback and the ability to adjust the treatment plan accordingly.

To date, computer-aided dynamic navigation has been utilized primarily within the field of dental implantology. This technology has improved accuracy of implant placement, making the procedure more favorable and predictable (35,36). Endodontic access cavities performed via a dynamic navigation method have been found to be more accurate compared to conventional freehand methods, although this conclusion was drawn from a non-standardized extracted tooth study that used an older generation of Navident (ClaroNav) which is now outdated (44).

The results obtained in this *in vitro* study support the implementation of computer-aided dynamic navigation (utilizing trace registration technology) for endodontic access cavity preparation. In this study, the computer-aided dynamic navigation system was applied to validate this technique in regard to endodontic access cavities and to evaluate the following: ability to successfully locate the canal space, the frequency of unsuccessful attempts in canal identification, the frequency of perforations, the amount of tooth structure removed via volumetric analysis, the time necessary for canal location and negotiation and operator improvement over time.

<u>1). Ability to successfully locate the canal space:</u>

The operator's ability to locate the canal space is critical to facilitate debridement of the root canal system. In this study, all canal spaces were located within the freehand treatment groups (20/20) and in all but two teeth within the dynamic navigation treatment groups (18/20). Typically, in freehand treatment attempts in a clinical setting and with no computer-assisted guidance option, the operator is not likely to cease the attempt in canal location unless the operator deems the tooth non-restorable. Thus, careful canal location is likely achieved as it did in this study, but may in turn result in the removal of more tooth structure (15). Among the dynamic navigation treatment attempts, the treatment was ceased by the operator when the target depth was reached according to the pre-planned access. Although the operator may be able to easily make an adjustment to locate the canal space based upon radiographic feedback and direct visualization, this modification was not executed in this study so that the technique could be fairly evaluated according to the pre-planned access within the dynamic navigation software.

2). Frequency of unsuccessful attempts in canal identification:

The unsuccessful attempts occurred within one mandibular dynamic navigation treatment tooth (NL-7) and one maxillary dynamic navigation treatment tooth (NU-10). Postoperative periapical and CBCT images obtained from the unsuccessful access attempt within the seventh mandibular dynamic navigation treatment tooth (NL-7) exhibited a conservative preparation in both the facial-lingual (F-L) and mesiodistal (M-D) dimensions yet the access deviated slightly toward the lingual and mesial surfaces of the root apically. Postoperative periapical and CBCT images obtained from the unsuccessful access attempt within the tenth maxillary dynamic navigation treatment tooth (NU-10) exhibited a conservative preparation in both the F-L and M-D dimensions yet deviated slightly toward the facial and distal surfaces of the root apically. The operator was confident the canal space could have been located in both unsuccessful attempts with a minor manual modification; however, the attempt was ceased once the target depth was reached within dynamic navigation software.

Both instances in which canal space was not located occurred when using the dynamic navigation treatment method. The navigation system had placed the bur in extremely close proximation to the canal in both of these instances as the access was just shy of canal space. Perhaps this occurred as the apical portion of the access was planned flush with the coronal extent of the canal space. This may be easily addressed if minor adjustments are made in the planning process to extend the access preparation further apically into canal space to ensure canal space is successfully located. The implant literature reports horizontal and vertical deviation errors of approximately 1.0 mm when using dynamic navigation technology (36). This may explain why a canal may not be located after execution of access with a dynamic navigation treatment method. Additionally, there is inherent human error with any drilling procedure (45).

3). Frequency of perforations:

When preparing an endodontic access cavity in an anterior tooth case exhibiting PCO, procedural mishaps, such as root perforation, are much more likely to occur (15). As this can affect long-term prognosis of a tooth (15,46), minimizing iatrogenic damage is very important. Frequency of perforations were noted and compared between freehand and dynamic navigation treatment groups. Of the three perforations that resulted in this study, two occurred within the freehand treatment groups (2/20) and one within the dynamic navigation treatment groups (1/20). The access perforations took place within one maxillary freehand treatment tooth (FU-5), one mandibular dynamic navigation treatment tooth (NL-7) and one mandibular freehand treatment tooth (FL-10). Postoperative periapical and CBCT images obtained from the perforated fifth maxillary freehand treatment tooth (FU-5) exhibited a somewhat conservative preparation in the M-D dimension yet an excessive amount of tooth structure removed in the facial-lingual F-L dimension. The perforation occurred facially within the middle third of the root. Postoperative periapical and CBCT images obtained from the perforated seventh mandibular dynamic navigation treatment tooth (NL-7) exhibited a conservative preparation in the facial-lingual F-L and M-D dimensions yet the access deviated slightly toward the lingual and mesial surfaces of the root apically. The perforation occurred toward the mesiolingual within the middle third of the root. Postoperative periapical and CBCT images obtained from the perforated tenth mandibular freehand treatment tooth (FL-10) exhibited a conservative preparation in the F-L and M-D dimensions. The perforation occurred distally within the middle third of the root.

When treating teeth with dynamic navigation, obtaining and maintaining successful calibration of the patient and handpiece was found to be a crucial. On several occasions it was noted if the position of the jaw tag had inadvertently been altered in any way, the planned access was no longer accurate. In these situations, it is crucial to immediately recalibrate the jaw in relation to the new position of the jaw tag and to re-plan the access preparation. If the deviation is not corrected immediately, the operator may make a significant depth cut in an incorrect direction and correcting the preparation may be somewhat difficult as there is be loss of tactile sense at deeper depths. This likely explains the perforation within the dynamic navigation treatment group.

Perforations are naturally more common within mandibular incisor teeth likely due to their smaller size and thinner dentinal walls (15). This finding was consistent with this study, although there was no statistically significant difference. Additionally, a clinician will typically access an incisor tooth from a lingual approach to avoid removing facial or incisal tooth structure. Thus, it is a natural tendency for the position of the clinician's bur to angle in a more facial direction, leading to a greater chance of perforation and greater removal of tooth structure. When accessing mandibular incisors or teeth exhibiting PCO, it is useful to access these incisors via a more incisal or facial approach to allow for straight-line access (47). This tendency was exhibited in this study and the access preparation was modified more incisal and facially over time as the operator learned how to better manage these cases.

<u>4). Amount of tooth structure removed and operator improvement over time:</u>

There is more to evaluate regarding the prognosis of an endodontically treated tooth in addition to successful canal location and avoidance of procedural errors. Perhaps more importantly, it is imperative to minimize the removal of tooth structure as any unnecessary tooth structure removal will only further destabilize the tooth (28). In this study, volumetric analysis of tooth structure removed in each treatment tooth was calculated using ITK/SNAP DICOM viewer software. Figure 20 was constructed to provide a visual of the 3-D renderings of the preoperative tooth models and to illustrate the access tendencies of the two treatment methods in both tooth models. Although the 3-D renderings of access preparations within each treatment group did not exhibit similar dimensions as shown in *Figure 20* throughout the duration of the study, there was a tendency for the FU (*Figure 20b*) and FL (*Figure 20e*) treated teeth to exhibit greater volume preparation variation within the B-L dimension. This further illustrates the tendency of the operator to deviate in the B-L dimension more-so than a M-D dimension when endodontically accessing calcified incisors.

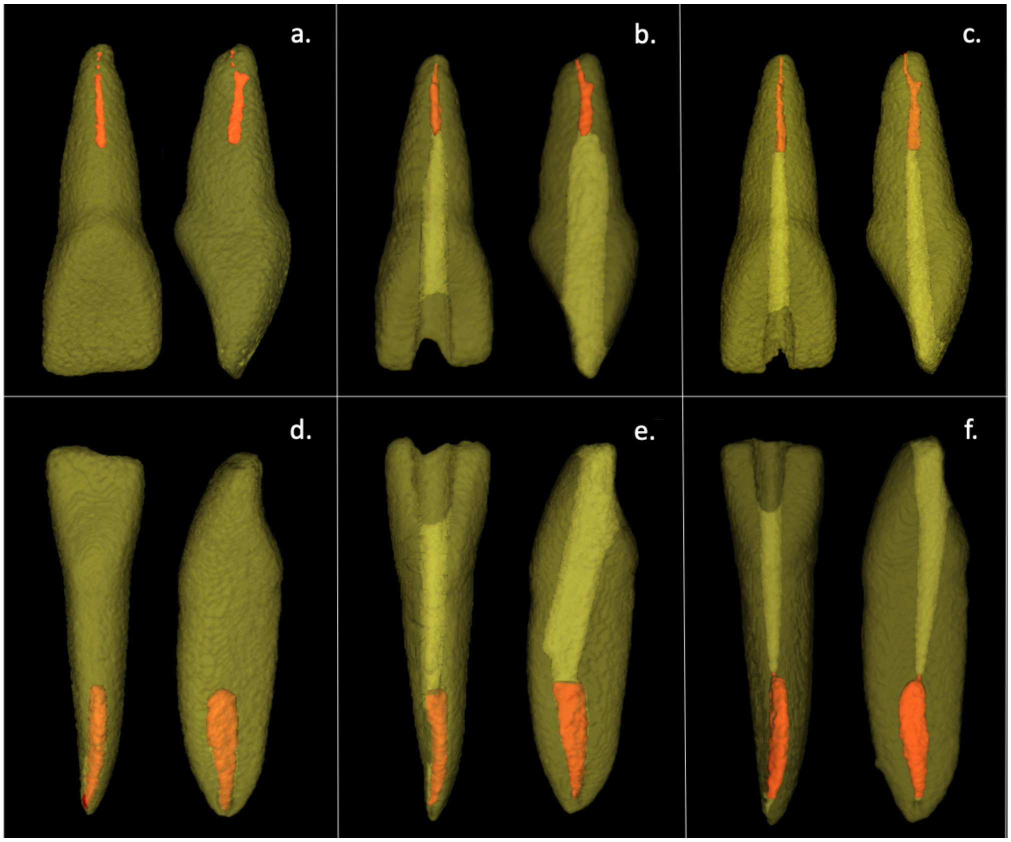

Figure 20: Digital 3D Renderings of Maxillary (#8) and Mandibular (#25) Pre- and Postoperative Tooth Models form Facial and Mesial Views

Figure 20a and *d* exhibit digital 3-D renderings of the maxillary (#8) and mandibular (#25) preoperative tooth models from facial and mesial views. The red color represents the pulp canal space that is located apically within the root. *Figure 20b, c, e* and *f* exhibit 3-D rendered images from the postoperative CBCT scans. The tan color represents the remaining tooth structure and the bright yellow color represents the prepared tooth structure to aid in visualization of the amount of tooth structure removed within the treatment attempt. *Figure 20b* and *e* show examples of maxillary and mandibular treatment teeth accessed with the freehand method and *Figure 20c* and *f* show examples of maxillary and mandibular treatment teeth accessed with the dynamic navigation method.

Averages of the mean tooth structure removed for each treatment group are shown in *Table 2*. A significant difference in the mean tooth structure removed was evident when comparing the freehand and dynamic navigation treatment methods. As the averages were similar for both mandibular treatment groups (NL and FL), differences were most significant when comparing the maxillary accessed teeth within the NU and FU treatment groups. On average, 2x more tooth structure was removed from a tooth within the FU group compared with a tooth within the NU. This is not only statistically significant, but also clinically significant. From this data, we can appreciate that maxillary anterior PCO teeth accessed with the dynamic navigation method show much more conservative access preparations than those accessed with the freehand method.

Figure 18 displays the preparation volumes from all access attempts (1-10). The amount of tooth structure removed was greatest within the FU treatment group (visual provided in *Figure 20b*). There was no significant difference in amount of tooth structure removed between the FL and NL groups. This is likely due to the size of the mandibular treatment tooth as well as increased visibility the operator has when treating a mandibular tooth versus maxillary tooth where more indirect vision is required.

Each data set shows a trend of improvement (gradually conserving more tooth structure) over time with each subsequent attempt (*Figure 18*). This learning curve is evident among freehand and dynamic navigation treatment groups and is consistent with a previous study's observations where a novice operator gained accuracy placing implants as a result of improved skills using computer-assisted dynamic navigation for implant placement (48). Inevitably, outliers exist within each treatment group and this is likely due to the methodology and sequencing of treatment sessions to better represent the operator's capability as they would have to refamiliarize with the techniques employed for accessing a tooth exhibiting PCO. The line of best fit representing the FU treatment group shows the greatest change over time among subsequent attempts. This illustrates the learning curve was most significant within the FU group and that the operator most significantly improved with the freehand method over time. The operator noticed by utilizing the dynamic navigation treatment technology, her freehand treatment technique improved as she was able to learn how to obtain ideal and minimally invasive straight-line access to the canal space. According to our findings, this technology may have potential in an educational setting to teach inexperienced operators how to obtain an ideal access.

5). Time necessary for canal location and negotiation and operator improvement over time:

The amount of time needed to successfully access the pulp canal space of a tooth exhibiting PCO is often significantly longer in duration compared with a tooth exhibiting a visible pulp chamber space. Not only is chair time of the essence, the operator may experience added stress when accessing teeth with this type of calcification as the canal is often located after a great deal of removal of root dentin below the level of the CEJ. With the implementation of a dynamic navigation system in endodontic clinical practice, an endodontic access should be more conservative, accurate and reduce the amount of treatment time needed to perform the procedure. Of course, additional time would be spent obtaining a preoperative CBCT, setting up the dynamic navigation software and equipment and planning the procedure, but this would be minimized with continued use and assistance from office staff.

The average time (minutes) for each treatment group is shown in *Table 3.* Time to complete the procedure was significantly related to the method, jaw and attempt number (*Table 4*). Overall, the freehand attempts took more time than the dynamic navigation attempts. Our findings are consistent with what one would expect, as it is likely an endodontic access performed via a freehand method would take a longer amount of time than would that with dynamic navigation. The maxillary tooth likely took significantly more time to prepare via freehand method due to the increased size of tooth and less direct visibility as there is an increased need for indirect visualization.

Figure 19 displays the estimated operation time (seconds) from all access attempts (1-10). The differences in treatment time were most significant when comparing the maxillary accessed teeth within the NU and FU treatment groups. There was no significant difference in operation time between the NU, FL and NL groups. Since the dynamic navigation treatment teeth preparations are pre-planned, the procedure ideally requires less treatment time in comparison to the freehand method where the operator has to use his or her best judgement and clinical skills to locate the canal space. Differences among the FL and NL groups may not show as much significance due to the size of the mandibular treatment tooth as well as increased visibility the operator has when treating a mandibular tooth versus maxillary tooth. The differences in volume and treatment time noted between the tooth models used in this study illustrate the point that an operator should be selective in the cases he or she chooses to use dynamic navigation. According to our findings, dynamic navigation did not prove to be significantly beneficial in accessing the mandibular tooth model.

Each data set shows a trend of improvement (gradually decreasing operation time) over time with each subsequent attempt (*Table 4*, *Figure 19*). This learning curve is evident among freehand and dynamic navigation treatment groups and is consistent with a previous study's observations where a novice operator gained speed placing implants as a result of improved skills using computer-assisted dynamic navigation for implant placement (48). Outliers do exist within each treatment group. This is likely a result of the methodology and sequencing of treatment sessions. By spreading out the treatment sessions, the operator loses the advantage of repeated exercise and haptic feedback. The line of best fit representing the FU treatment group shows the greatest change over time among subsequent attempts. This illustrates the learning curve was most significant within the FU group and that the operator most significantly improved with the freehand method over time. The operator gained haptic feedback with repetitive use of the dynamic navigation and observed that this technology trained her how to improve and perform a more ideal access with freehand techniques, thus reducing treatment time. Although only the FU treatment group showed a statistically significant decrease in operation time for each subsequent attempt, all other treatment groups seemed to follow this same trend. This was determined to be clinically significant as the operator exhibits improvement over time when using dynamic navigation.

Study Strengths:

This study consisted of several strengths in comparison to some previously executed studies. Use of identical 3-D printed tooth models allowed for fair and accurate comparisons. In addition, utilizing the same operator throughout allowed for evaluation of improvement with these techniques over time. More importantly, treatment sessions were spread out over time to reproduce a clinically relevant scenario as an operator may not be likely to use dynamic navigation routinely, but on an as needed basis for more difficult endodontic accesses.

This was the first study to implement the trace registration technology for dynamic navigation procedures for endodontic access. This new technology was proven successful and easy to use.

Study Limitations:

Several limitations were identified in this study. First, the 3-D printed tooth model lacks regional variation in color and anatomic landmarks that may guide the clinician during conventional canal location in natural teeth. Thus, the use of 3-D printed teeth can place the freehand technique at a slight disadvantage. The freehand techniques utilized to precisely locate a simulated calcified root canal will inherently generate errors in all parameters that may lead to higher substance loss or perforations. Another limitation may be the limited variation in teeth/models used. In using the same two tooth models for all attempts, the operator may be able to more easily identify techniques employed to treat the tooth, inevitably increasing success of treatment over time. This assessment could be further evaluated with the addition of multiple operators. Last, as we did not calculate accuracy of the methods used to access the teeth in this study, we relied on volumetric analysis to determine how conservative an access was. By strictly evaluating the prepared tooth structure or volume removed from a tooth in access preparation, this does not address the restorability of the tooth.

Learning points:

There are several learning points that can be drawn and implemented in clinical practice from this study. As observed in the freehand treatment preparations, an operator is much more likely to deviate internally in a B-L dimension rather than the M-D dimension. The operator is likely to make this mistake by initiating a conventional lingual rather than incisal access. The main bur used in this study (859 FGSL) was very useful in creating an ideal straight-line access from the incisal edge. The 859 FGSL bur is a narrow surgical length tapered diamond bur and is traditionally utilized for crown preparations (*Figure 21*). This is not a bur an operator would traditionally use for such an access, but it proved to be very useful for both freehand and dynamic navigation treatment methods. This bur allowed the operator greater visibility and with increased use and familiarity seemed to help achieve more conservative access preparations.

Figure 21: 859 FGSL Bur

Over time, the operator learned in order to obtain ideal straight-line access to the pulp canal, a more incisal or facial approach was necessary to conserve the most amount of tooth structure possible. This was exhibited by the dynamic navigation method and with increased use of this technology, the operator also noticed an improvement in the freehand access treatments. It is reassuring that with increased use of both techniques, there was improvement made over time.

Future Directions:

Overall, dynamic navigation technology shows promise for endodontic access procedures; however, it is more time consuming due to set-up, planning, unfamiliarity and the overall complexity of the system. There is a significant learning curve involved to establish confidence within the operator when using this technology.

The trace registration technology shows promise, yet improvements could be made to the jaw tag design to allow for greater stability and ultimately decrease the need to perform recalibration procedures. Future studies are needed to streamline planning protocols, determine the accuracy of endodontic access cavities performed in calcified teeth with dynamic navigation technology and validate our findings.

Conclusion

Within the limitations of this *in vitro* study, computer-aided dynamic navigation technology has the potential to be a safe alternative in achieving dentin conservation for locating calcified canals in comparison to conventional freehand technique.

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