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Accuracy of Dynamic Guidance System in Endodontic Access of Anterior Teeth - ex vivo Analysis

Kyan Salechi
Medical University of South Carolina

Accuracy of a dynamic guidance system in endodontic access of Anterior teeth – ex vivo analysis

By

Kyan Salehi, DMD

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Department of Oral Rehabilitation

Division of Endodontics

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Approved by:

Chairman, Advisory Committee

Theodore Ravenel

Zachary P. Evans

Robert G. Gellin

Table of Contents

List of Tables

List of Figures

ABSTRACT

Kyan Salehi, DMD. Accuracy of a dynamic guidance system in endodontic access of Anterior teeth – ex vivo analysis.

Aim: To measure the accuracy, we will be evaluating the position deviations and angular deviations of endodontic access preparations compared with the digital file plan for the guided access. **Material and Methods:** 24 extracted human anterior teeth (4 maxillary canines, 4 mandibular canines, 8 mandibular incisors, and 8 maxillary incisors) were mounted into acrylic resin to mimic the position in the human jaw. Pre-op CBCT images of the models were acquired and imported into the X-Nav system software. Virtual endodontic files were custom created in the software by adjusting the diameter of the “implant” to 0.5 mm, with lengths ranging from 7-14 mm to allow virtual placement with coronal termination of the file near the natural tooth occlusal surface. The enamel of the path of the access is first removed using a high-speed drill and a #4 round bur and subsequently 34mm size #1 Munce with the 1:1 dental surgical electric handpiece was used to drill through the designed access in the proper orientation. Post-op CBCT images were taken and evaluated for angular deviation via access design and endodontic file placement deviations. **Results:** Subjective analysis confirmed passive straight line access with a #8 K-file through the access for all canals and CBCT images were captured. Images were repeated with files in the canal after decoronation of teeth. No significant difference was found in file angular deviations. Overall files angular deviation was 2.75 ± 2.21 degrees. There was a significant difference found among maxillary canine vs mandibular canines (1.34 ± 1.32 degrees and 5.61 ± 1.63 degrees, respectively) with a p-value=0.0064. A significant difference was found among each tooth type when comparing the drill depth needed to achieve passive access with endodontic files. There was significant difference found when comparing maxillary canines to mandibular incisors. The average drill depth for maxillary canines was 12.75 ± 2.06mm, maxillary incisors was 12 ± 1.93mm, and mandibular incisors 8.05 ± 0.97mm. **Conclusion:** The dynamic guide system proved to be highly accurate in accessing root canals of anterior teeth while creating a highly conservative access design. The accuracy was consistent among all anterior teeth without any significant difference. All canals were located after the endodontic access was completed using the software. Further research will be needed to study the practicality of the system in a clinical setting. The system does have a learning curve of 3-4 teeth and the system can be very useful in situations with highly calcified teeth where deep access will be required to locate canals.

INTRODUCTION

The main goal of endodontics is the successful elimination of the etiology of apical periodontitis. This etiology is bacteria (Kakehashi et al.1965), and the treatment consists of mechanical (Ingle & Zeldow 1958, Bystrom & Sundqvist 1981) and chemical (Bystrom & Sundqvist 1983, Dalton et al. 1998) treatment of the root canal space in order to achieve the best prognosis (Farzaneh et al. 2004). Accomplishing such procedure will result in the removal of tooth structure, both internally and externally, in order to achieve proper access to the root canal space.

As an endodontic clinician, one of the goals of root canal therapy is to avoid the removal of excessive tooth structure and to achieve proper, straight-line access to the root and the root canal space. This would create proper visual working space; more importantly the access would minimize the stress that would be applied to rotary instruments during mechanical preparation (Bahacall et al 2005). Mannan et al. (2001) studied the effects of cavity preparation on the degree of instrumented root canal space on maxillary anterior teeth and found that a straight-line access resulted in a greater proportion of the root canal wall to be instrumented compared to the traditional lingual access approach.

Access designs are different for each tooth in the dentition. Posterior molars and premolar are typically accessed from the occlusal level. Anterior teeth are traditionally accessed from the lingual aspect for esthetic purposes (Mauger 1999). Each tooth has its challenges; accessing molars requires the proper un-roofing of multiple canals for cleaning and shaping as the prevalence of multiple canals is much more prevalent in these teeth.

Anterior teeth, with an exception for lower anteriors, typically have only one canal (Vertucci 1984) and the access to these canals tend to be more straightforward. Another advantage in anterior access versus molar access is that less tooth structure is removed, which directly influences fracture resistance post restoration (Linn & Messer 1994) (Ramirez-Sebastia et al. 2014).

Unlike molars, anterior teeth do not typically undergo full coverage restoration after a root canal therapy due to the lack of occlusal forces from opposing (AAE Colleague of Excellence 2004). As a result, preserving tooth structure is an important aspect of endodontic access in the anterior dentition. Accessing anterior teeth becomes challenging because of its small size and any deviation from a straight-line access can irreversibly damage the tooth.

A lingual or palatal access for mandibular and maxillary anterior teeth would require the removal of excess cervical dentin in order to achieve a straight-line access. A study by LaTurno et al. (1985) revealed that a more labial approach to accessing these teeth would allow for a more unobstructed pathway for endodontic procedure, therefore making the procedure more efficient and increasing endodontic success rate. This buccal, straight-line approach was recommended by other authors as well (Madjar et al. 1989; Clements et al. 1991).

Additional challenges can be encountered with mandibular incisors because of the prevalence of multiple canals and their extremely small size. Benjamin and Dowson (1974) reported 41.4% prevalence rate for two canal mandibular incisors. Locating these second canals typically requires excessive removal of the lingual dentin to acquire proper access for debriding a second, lingual canal (Mauger et al. 1999). Mauger et al. (1999) also found that 27.6% of mandibular incisors had a more facial endodontic access and 72.4% ideal straight-line access were situated more incisal.

Typically, accessing a tooth is a straightforward task for a skilled clinician that is able to clearly visualize the pulp chamber and pulp canal space on a digital radiograph. This task can become challenging, even for the most skilled clinician, when the pulp chamber and pulp canal are not visible on a standard, digital radiograph. In such cases as calcified teeth or teeth with obliterated canal space as a result of trauma, difficulties can be encountered (AAE Colleagues for Excellence 2010).

Minimally invasive access designs and their implications to the prognosis of the tooth has been researched and challenged in recent years. Zhang et al. recently published a study in 2019 regarding the effects of different endodontic cavities on the fracture resistance of first maxillary molars and found that conservative endodontic cavity resulted in the increase of fracture resistance of endodontically treated teeth. Similar results were found by Allen et al. (2018) when they compared the stress resistance of teeth treated through minimally invasive access versus traditional straight-line access.

Clark and Khademi (2010) presented case studies and guidelines for a minimally invasive approach in endodontic access as a means to preserve tooth structure and cervical dentin. They viewed the traditional approach as a flawed and outdated practice. A modified approach to such access has recently been proposed and has been termed the “ninja” access (Belograd 2016). Such access designs are essentially performed free-handed and require very skilled clinicians with many years of clinical experience to achieve such access.

In order to properly design a minimally invasive endodontic access, a thorough understanding of the pulp chamber and the canal space anatomy is required. One tool that helps a clinician acquire such information preoperatively is the use of digital radiographs, which include bitewings (BW) and periapical (PA) images. Robinson et al (1989) recommended BW radiographs for assessing coronal pulp chamber anatomy. These images provide the clinician the information necessary to successfully navigate the tooth during treatment and minimize the removal of excess tooth structure that may-be a result of an off-angle access that would require mid-operatory correction.

There are limitations with digital PA radiographs. Nattress and Martin (1991) showed that standard PA radiographs failed to detect twin canals in mandibular molars in 1/3 of the cases. With the emergence of Cone Beam Computed Tomography (CBCT), the 2-dimensional limitations with a digital radiograph are taken away and the accuracy of interpreting anatomical variations increases (Ludlow et al. 2007) (Strateman et al. 2008) (Scarfe et al. 2009). Azim et al. (2014) found that CBCT images can be used to precisely measure pulp chamber landmarks before accessing.

With the widely accepted usage of CBCT in the field of endodontics and the emergence of new innovative technologies such as 3D printing, clinicians have been able to merge these tools to invent new techniques to treat teeth with endodontic needs. Such techniques consist of the utilization of static guides or CBCT generated dynamic guidance.

Static guidance consists of generating 3D models that allow the clinician to properly and accurately operate in critical areas of the mouth. This technique has been widely used by clinicians in the placement of implants (Sarment et al. 2003) (Di Giacomo et al. 2005) as it allows depth and angulation control for the clinician to place the implant in the desired area of the edentulous space. In contrast, dynamic guidance in implant placement is a recent technology that utilizes CBCT scans and optically-driven guidance system to place implants (Mischkowsk et al. 2006) (Block & Emery 2016). Dynamic guidance relies on the free movement of the clinician to guide the treatment rather than a static model that would guide the handpiece/drill.

Both systems are fairly new techniques in the field of dentistry and their use and accuracy have been shown in implant placement. Klein and Adams (2001) suggested the use of milled CT-based drilling guides as a solution to the common problem of poorly positioned implants being placed free-hand. Sarment, et al. (2003) reported the accuracy of implant placement with the use of 3D-printed surgical guides was superior to traditional techniques. These studies spawned further research on the use of static guidance and their accuracy in surgical implants (Arishan et al. 2014) (Hoffman et al. 2005) (Nickenig et al. 2010).

Pinskey et al. in 2007 was the first to report the usage of CBCT based drill guides in endodontics and their usefulness in guided periapical surgery. Their results showed that guided access allowed for consistently accurate and reliable access to the apex while minimizing the risks of damaging vital structures. Buchgreitz, et al., and Zehnder, et al., in 2016 applied CT-based static guides to endodontic access preparation.

Over the past few years, there have been numerous case studies and ex-vivo studies confirming the accuracy and benefits of utilizing CT-based static drill guides for endodontic access (Buchgreitz, Buchgreitz, & Bjorndal, 2018) (Connert, Zehnder, Amato, Weiger, Kuhl, & Krastl, 2017) (Lara-Mendes, Barbosa, Santa-Rosa, & Machado, 2018) (Mena-Alvarez, Rico-Romano, Lobo-Galindo, & Zubizarreta-Macho, 2017) (Nayak, Jain, Kankar, & Jain, 2018) (Torres, Shaheen, Lambrechts, Politis, & Jacobs, 2018). These studies show that the challenges previously mentioned, can be overcome with the accuracy of these systems.

As accurate as the static guided models have been shown to be in endodontic access preparation, they do have their limitations and concerns.

The complex workflow of available systems and their cost have prevented broader adoption (Anderson, Wealleans, & Ray, 2018). Also, Anderson et. al. reported a disconnect between CBCT scans and fabrication of 3D models. The average CBCT slice thickness used in endodontic applications can be as small as 0.076 to 0.6 mm, which is much thinner than the recommended maximum limit of 1 mm for 3D printing (Kim et al. 2016). A Small field of view is the preferred scan modality in endodontics with CBCT, but a small field of view (FOV) may not capture enough crown morphology to recreate the patient's occlusion during guide fabrication.

Static guides have also been noted to have the following in-treatment limitations when being utilized for endodontic access (Emery et al. 2016)(Buchanan LS 2018) (Block & Emery 2016):

1. Lack of inter-occlusal space for the guide and the drill, especially on posterior teeth.
2. Inability to perform same-day treatment, as static guides require printing and modifications. Extra time is added if guides are milled by an outside laboratory, which can also increase the risk of operator error.
3. Inability to alter treatment plan during the procedure, if needed

4. Guided rings don't allow for use of a bur with high-speed handpiece, as of today
5. Multiple drill guides are needed when treating multi-canal teeth
6. The need for periodic x-rays during treatment to confirm the drill path.
7. The inability for proper irrigation during access in order to minimize heat damage to the tooth that is created from active drilling.

Dynamic optically-driven guidance systems have the potential to minimize some of the limitations of the static guides. The accuracy and efficiency of this system in implant placement have been shown to be similar to static guidance in studies published by Widmann et al. (2010), Block & Emery (2016) and Emery et al. (2016). More importantly, dynamic guided systems have more flexibility for the clinician to change a surgical plan during clinical situations (Block & Emery 2016).

Dynamic navigation use for endodontic access has been a recent proposition and it has not been thoroughly explored. In our search, only a few case studies of dynamic navigation in endodontics have been reported (Buchanan et al. 2017) (Buchanan LS 2018). Only recently, a study by Chong et al. (2019) has shown the accuracy of locating canals using a dynamic guidance system.

The aim of this study is to evaluate the accuracy of endodontic access of anterior teeth via the guidance of the X-Guide Surgical Navigation System (X-Nav Technologies, LLC, Lansdale, Pa). To our knowledge, this is the first ex-vivo study to evaluate the accuracy of endodontic access using this dynamic guidance system. To measure the accuracy, we will be evaluating the position deviations and angular deviations of endodontic access preparations compared with the digital file plan for the guided access. We hypothesize that the deviation of our access will be minimal and insignificant in comparison to the anatomical straight-line access of the accessed teeth using the dynamic guidance system.

MATERIAL/METHODS

The study design was approved and conducted at The Medical University of South Carolina in the department of Endodontic Graduate Studies and completed by the authors, who were second year Endodontic residents.

Dentoform Fabrication:

24 extracted human anterior teeth (4 maxillary canines, 4 mandibular canines, 8 mandibular incisors, and 8 maxillary incisors) with minimal caries or restorative history were acquired in compliance with the Medical

University of South Carolina Institutional Review Board. Rubber model former mold (*Buyamag, Carlsbad CA)* were used to mount the extracted teeth in their proper arch position in order to mimic the position in the human jaw. Rope wax (*Heraeus, South Bend IN*) was used to encase the apical extent of the teeth in order to prevent encroachment of resin in the canal space. The roots and the rubber model mold were encased in a self-curing acrylic resin JET tooth shade powder and liquid, which is traditionally used for making temporary crown and bridge restorations (*Lang Dental, IL*) in order to create full arch custom dentoforms (Figure 1).

Imaging:

Following the protocol by X-Nav Technologies, LLC, before acquiring CBCT of models, a bite registration device, X-Clip with three metal, ball fiducials (X-Nav Technologies, LLC) was placed on the arch just posterior to one of the second molars (Figure 2). Following the manufacturer recommendation for placement of the X-clip, the clip was placed in a hot water bath until the impression material turned from white to a clear color. The clip would be placed in a manner to cover at least two teeth for greatest stability. If there were no second tooth present, a tooth was molded posterior to the 1st molar from the acrylic resin.

Vaseline was placed over the acrylic teeth in order to prevent the X-clip impression material from adhering to the resin material. The clip was then firmly pressed on the dentoform and removed immediately and immersed in an ice bath for approximately 20 seconds. The X-Clip was then confirmed for proper placement on the dentoform and the dentoforms were then scanned with the Planmeca ProMax 3D Max CBCT machine (Planmeca OY, Helsinki, Finland) on the setting Jaw Mode at 90Kv, 10mA, and 150 micron slices using the Planmeca Romexis software (version 5.2.1.R). After the scans, X-clips were removed, labeled, and stored for use during treatment.

Planning Virtual Endodontic Access Design:

The planning stage was performed by two 2nd year endodontic residents under the direction of two Periodontics faculty members.

The DICOM data sets of each jaw model were exported from the Romexis software and uploaded into the X-Nav software. The software was used to define the arch "spline" and implant dimensional manipulation. Virtual endodontic files were custom created in the software by adjusting the diameter of the "implant" to 0.5 mm, with lengths ranging from 7-14 mm to allow virtual placement with coronal termination of the file near the natural tooth occlusal surface. The X-Nav software currently allows for only a single implant to be placed associated with each tooth number, but you can plan multiple implants at each site by planning for adjacent teeth and dragging the implant to the desired site. This enables treatment planning of endodontic access for multi-canal teeth. For example, on a lower molar #30, the distal canal was #30, the mesiolingual canal was #31 and the mesiobuccal canal was number #32. The software allows for simultaneous visualization of multiple CBCT views (Axial, Sagittal, and Coronal) in order to properly orient the virtual implants into the coronal 1/3 of the canal and to allow straight vector access based upon the trajectory of the coronal aspect of each canal. The straight virtual files were placed to allow straight vector access based upon the trajectory of the coronal aspect of each canal (Figure 3).

Model Mounting and Treatment Simulation:

The teeth/dentoforms were hydrated in 0.9% normal saline for 24 hours prior to accessing. Dentoforms were mounted on a post and attached to the dental operatory chair. This set-up was done to simulate a clinical treatment scenario (Figure 4). The X-Guide machine was oriented in a manner that would allow proper visualization of the guided screen by the operator and to allow an assistant to be positioned during treatment to administer proper irrigation (Figure 4).

***System Calibration*:**

In order to provide dynamic guidance during treatment, the X-Guide tracks the motion of two dynamic reference frames (DRFs). One frame is attached to the patient via the X-clip bite registration device (patient tracker), and the other is attached to the surgical handpiece (handpiece tracker). Each DRFs have their corresponding fiducials that are registered by the guided camera. These reference frames must be calibrated before treatment. The patient DRF calibration determines the relationship between the patient and the CT fiducials. Calibration of the handpiece allows the system to determine the relationship between the handpiece and the axis of the drill.

Per the manufacturer's instructions, the X-guide software requires a series of calibration steps and notifies the operator of a successful calibration of each step. Proper calibration is done by ensuring that the overhead X-Guide cameras were in a position to read the DRF's. The distance of the cameras to the DRF's, as prompted by the X-Guide machine software, is between 60cm-80cm. Handpiece tracker and Patient Tracker are calibrated separately with each calibration taking about 1-2min. The drill bit length is calibrated via the provided Go-Plate and must be calibrated each time the handpiece is out of the view of the guided cameras for 10-15 seconds.

The successful calibration will allow registration of the patient tracker and handpiece tracker to the 3D plan for real-time guidance. The information is fed into a multi-window video feed which allows the operator interactive turn-by-turn guidance and the ability to improve every movement of the handpiece during implant guided guidance (Figure 6).

Accessing teeth:

A latch fit 1:1 dental surgical electric handpiece (W&H WS-56, Bürmoos, Austria) was used for the drilling at 40,000 RPM (Figure 7). Before using any bur with the handpiece to drill on the teeth, the drill bit length is first calibrated with the Go-Plate and then the surrounding teeth near the targeted access site are touched to confirm the system's indication of the position and that it corresponds to the CBCT image displayed on the interactive monitor. Virtual endodontic files were custom created in the software by adjusting the diameter of the "implant" to 0.5 mm, with lengths ranging from 7-14 mm to allow virtual placement with coronal termination of the file near the natural tooth occlusal surface.

A #4 round bur was the initial bur used with the latch fit 1:1 dental surgical handpiece (W&H WS-56, Burmoos, Austria) in order to create an initial pilot in proper orientation of the designed virtual implant. Next, a #4 round bur on a high-speed handpiece is used to drill through the enamel while keeping the same orientation as the planned implant. At the time when this research was being conducted, it was not possible to calibrate a high-speed handpiece with the X-Guide system, therefore the proper orientation is judged by the operator and only the enamel layer was removed with the high-speed handpiece.

Once the enamel was removed, a 34mm size #1 Munce bur (head diameter of 0.8mm) (CJM Engineering) was once more calibrated with the X-guide system with the 1:1 dental surgical electric handpiece and subsequently used to drill through the designed access in the proper orientation. The reason a #4 round burs was initially used was to avoid any contact of the shaft of the Munce burr (0.7mm-1mm in variable thickness) to the walls of the access and to avoid overheating the drill. The drilling was performed in increments with a copious amount of irrigation to prevent overheating of the drill and minimizing the accumulation of debris in the access.

Once the proper depth was reached, which was determined by the planed design with the X-guide software, the bur reached the apical aspect of the desired length, the software prompted the operator to stop. The bur was removed and the access to the canal orifice was confirmed by passively negotiating a 25mm #10 K file through the small access into the canal without any obstructions.

Post access analysis:

After completing access to all teeth, CBCT of the dental segments were taken in the same format as the initial CBCT pre-planning stage. Each access hole was evaluated for passive canal access using a #8 K-file, and additional CBCTs were captured with the files in place (Figure 8). Only one file was placed in each tooth per image capture to reduce radiographic artifact.

After the CBCT with the #8 K-file in place was completed, the teeth were decoronated using a high-speed handpiece with a tapered diamond bur at the level of CEJ. A second round of CBCT images was taken with the decoronated teeth with a #8 K-file passively placed in each of the uncovered roots. This would allow us to capture the true file emergence.

To measure the accuracy of our straight-line access design by the X-Guide, we compared the deviation of our access from the natural path of the physical canal. To measure this deviation, we developed a method to overlap the two sets of CBCT's (CBCT with K-files placed in the tooth before and after decoronation) and measure the angle of deviation created by the superimposed K-files from each CBCT images. This measurement is noted as File Angular Deviations.

Variation was measured from the first perceivable point of the vertex (point prior to separation), and rays were marked on the same side of the files to yield an angulation. For each canal, the files were observed circumferentially and the direction of greatest variation was recorded between the files as the angle deviation.

To determine the accuracy of our drilled accesses, the preoperative virtual access plan and a postoperative CBCT scan were superimposed. In this process, using the X-Guide implant planning software, a trained engineer from X-Nav first identified the precise path of the drilled access in the postoperative CBCT scan. Next, the preoperative and postoperative CBCT scans were registered by aligning the sawbone structure in each scan via a rigid transformation. To generate the registration, polygonal meshes representing the outer Sawbones surfaces were extracted from the pre- and post-operative CBCT scans via conventional iso-surface thresholding techniques. The meshes were then cleaned of any artifacts and aligned in the open-source MeshLab software suite. Using the rigid transform defined by the MeshLab registration, the virtual preoperative access path was projected onto the postoperative CBCT scan, where its position and orientation are compared with those of the drilled access. To determine any deviations, we compared three different measurements: The overall Access Angular

Deviation, Coronal Deviation, and Cutting Tip Deviation (Figure 9).

Data and Statistical Analysis:

For the comparisons of maxillary teeth to mandibular teeth, a Wilcoxon Rank Sum Test was used for the outcomes of Access Angular Deviation, Coronal Deviation, Cutting Tip Deviation, and Drill Depth. A T-test was used for File Angular Deviation. P-values were considered to be significant if they were less than 0.05.

For the comparison of tooth type, an Analysis of Variance (ANOVA) model was used. All outcomes were log-transformed for normality except File Angular Deviation. All descriptives are presented on a normal scale. If the main effect was significant for Tooth Type, post-hoc comparisons were presented with a Tukey adjustment. The rest of the comparisons (Tooth type within Maxillary/Mandibular and Anterior/Posterior within Maxillary/Mandibular) used an Analysis of Variance (ANOVA) model with each main effect and their interaction in the model. All outcomes were log-transformed for normality except File Angular Deviation. All descriptives are presented on the normal scale. If the interaction term was significant, post-hoc comparisons were presented with a Tukey adjustment.

RESULTS

One mandibular central incisor was damaged during the preparation of our models and could not be included in the access design. Another central incisor was excluded from the study due to the clinical crown completely fracturing off during access. Our final number of teeth used for statistical analysis was 22.

After every access was terminated at the designated implant access length, a #8 k-file was passively directed to the canal entrance for every canal. From the standpoint of direct clinical canal access, we achieved 100% success and accuracy of all canals.

When comparing each tooth type (i.e. canine vs incisors) in each quadrant (i.e. maxillary vs mandibular)

There was a significant difference found among maxillary canines vs mandibular canines with a p-value=0.0064 when comparing access angular deviations. The mean deviation in maxillary canines was 1.34 $\pm$ 1.32 degrees and mandibular canines was 5.61 $\pm$ 1.63 degrees (Table 1).

		N	Mean	Median	Std Dev	5th Pctl	95th Pctl
Mand	**Canine**	4	5.61	5.09	1.63	4.3	7.96
	Incisor	6	3.17	2.92	1.75	0.62	5.99
Max	**Canine**	4	1.34	0.73	1.32	0.58	3.32
	Incisor	8	2.34	2.21	1.01	0.96	4.41

Table 1. **Access Angular Deviation** (degrees) measurements and analysis using ANOVA

There was no significant difference found when comparing coronal deviations and cutting tip deviations (Table 2 and Table 3 respectively).

		N	Mean	Median	Std Dev	5th Pctl	95th Pctl
Mand	**Canine**	4	0.99	0.87	0.74	0.21	1.99
	Incisor	6	0.57	0.54	0.32	0.22	0.99
Max	**Canine**	4	0.36	0.23	0.35	0.11	0.87
	Incisor	8	0.46	0.5	0.16	0.22	0.65

Table 2. **Coronal deviations** (mm) from our planned access measurements and analysis using ANOVA

		N	Mean	Median	Std Dev	5th Pctl	95th Pctl
Mand	**Canine**	4	0.48	0.44	0.36	0.13	0.89
	Incisor	6	0.36	0.33	0.17	0.17	0.64
Max	**Canine**	4	0.33	0.18	0.36	0.1	0.87
	Incisor	8	0.25	0.19	0.13	0.13	0.44

Table 3. **Cutting Tip Deviation** (mm) from planned access measurements and analysis using ANOVA

There was a significant difference found among each tooth type when comparing the drill depth needed to achieve passive access with endodontic files. There were significant differences found when comparing maxillary canines to mandibular incisors (p-value=0.0007) and maxillary incisors to mandibular incisors (p-value=0.0004). The average drill depth for maxillary canines was 12.75 $\pm$ 2.06mm, maxillary incisors was 12 $\pm$ 1.93mm, and mandibular incisors 8.05 $\pm$ 0.97mm (Table 4). It required more access depth to achieve proper access to orifice of canals for maxillary canines and incisors compared to mandibular canines and incisors.

		N	Mean	Median	Std Dev	5th Pctl	95th Pctl
Mand	**Canine**	4	9.23	9.2	1.03	8	10.5
	Incisor	6	8.05	8.1	0.97	6.6	9.5
Max	**Canine**	4	12.75	13	2.06	10	15
	Incisor	8	12	12	1.93	10	15

Table 4. **Drill depth measurements** (mm) required to achieve passive access to canals

There was no significant difference found among File Angular deviations as well (Table 5).

File Angular Deviation							
		N	**Mean**	**Median**	**Std Dev**	**5th Pctl**	**95th Pctl**
Mand	**Canine**	4	4.03	3.41	1.88	2.64	6.67
	Incisor	6	2	1.1	2.16	0.01	5.06
Max	**Canine**	4	3.44	4	2.47	0.02	5.73
	Incisor	8	2.34	2.07	2.15	0.01	5.78

Table 5. **File Angular Deviation** comparison among tooth type (p-value = 0.6014)

Tooth Type Analysis (Canine vs Incisors)

When comparing canines versus incisors, there were no significant difference found when comparing Access Angular Deviation (lowest value was 0.58 degrees in maxillary canine and highest value was highest value is 7.9 degree in mandibular canine), Coronal Deviation (lowest value was 0.10mm in maxillary canine and 1.99mm in mandibular canine), Cutting Tip Deviation (lowest value was 0.09 mm in a maxillary canine and highest value was 0.89mm in a mandibular canine), Drill Depth (lowest value was 6.6mm in a mandibular incisor and highest values was 15mm in a maxillary incisor), or File Angular Deviations (lowest value was 0.01 degrees in a mandibular incisor and highest value was 6.67 degrees in a mandibular canine). The results are displayed in table 6. Coronal and Cutting Tip average tip deviations displayed very minimal angular differences for each tooth type, which corresponds to the accuracy of the dynamic system achieving precision results.

Access Angular Deviation p-value=0.4549						
Tooth type	**N**	**Mean**	**Median**	**Std Dev**	**5th Pctl**	**95th Pctl**
Canine	8	3.47	3.81	2.66	0.58	7.96
Incisor	14	2.7	2.67	1.38	0.62	5.99
Coronal Deviation p-value=0.7043						
Tooth type	**N**	**Mean**	**Median**	**Std Dev**	**5th Pctl**	**95th Pctl**
Canine	8	0.67	0.54	0.63	0.11	1.99
Incisor	14	0.51	0.54	0.24	0.22	0.99
Cutting Tip Deviation p-value=0.7218						
Tooth type	**N**	**Mean**	**Median**	**Std Dev**	**5th Pctl**	**95th Pctl**
Canine	8	0.41	0.21	0.34	0.1	0.89
Incisor	14	0.3	0.25	0.15	0.13	0.64
Drill Depth p-value= 0.0213 (however, after adjustment for multiple comparisons, none of the post-hoc comparisons were significant)						
Tooth type	**N**	**Mean**	**Median**	**Std Dev**	**5th Pctl**	**95th Pctl**
Canine	8	10.99	10.25	2.41	8	15
Incisor	14	10.31	10	2.55	6.6	15
File Angular Deviation p-value= 0.0002						
Tooth type	**N**	**Mean**	**Median**	**Std Dev**	**5th Pctl**	**95th Pctl**
Canine	8	3.73	3.75	2.06	0.02	6.67
Incisor	14	2.19	1.64	2.08	0.01	5.78

Table 6. Canine vs Incisors comparison

Maxillary Anterior vs Mandibular Anterior

When comparing maxillary anterior versus mandibular anterior teeth, there were significant differences found in Drill Depth with a p-value of

<0.0001. On average, the Drill Depth for maxillary anterior teeth was found to be 12.25 ± 1.91mm compared to mandibular anterior drill depth of 8.52 ± 1.12mm.

There were no significant differences found when comparing Access Angular Deviation, Coronal Deviation, Cutting Tip Deviation, or File Angular Deviations (Table 7).

Access Angular Deviation							
		N	**Mean**	**Median**	**Std Dev**	**5th Pctl**	**95th Pctl**
Mand	**Anterior**	10	4.14	4.1	2.04	0.62	7.96
Max	**Anterior**	12	2.01	2.02	1.17	0.58	4.41
Coronal Deviation							
		N	**Mean**	**Median**	**Std Dev**	**5th Pctl**	**95th Pctl**
Mand	**Anterior**	10	0.74	0.69	0.53	0.21	1.99
Max	**Anterior**	12	0.43	0.44	0.23	0.11	0.87
Cutting Tip Deviation							
		N	**Mean**	**Median**	**Std Dev**	**5th Pctl**	**95th Pctl**
Mand	**Anterior**	10	0.41	0.33	0.25	0.13	0.89
Max	**Anterior**	12	0.28	0.19	0.22	0.1	0.87
File Angular Deviation							
		N	**Mean**	**Median**	**Std Dev**	**5th Pctl**	**95th Pctl**
Mand	**Anterior**	10	2.81	2.68	2.21	0.01	6.67
Max	**Anterior**	12	2.7	2.96	2.21	0.01	5.78

Table 7. Maxillary vs Mandibular Anterior comparison.

DISCUSSION

Clinically the X-Guide dynamic guidance system that was used in our study achieved highly conservative access on anterior teeth and terminated with precision to the canal orifices of the tested teeth. The overall Angular Deviation of our access drill path for all anterior teeth was 2.98 ± 1.57

degrees, compared to the planning angle. This deviation produced no significant difference in value when comparing tooth type (canines versus incisors); the deviation was extremely minimal in clinical perspective and was not considered clinically important. (lowest recorded deviation was 0.57 degrees and highest recorded deviation was 7.95 degrees).

To this date, there has been no study published that has reported the deviation in minimally invasive endodontic access via the dynamic guided system. Static guide systems have been utilized in endodontic access on anterior teeth that have shown similar accuracy. A case report published by Lara-Mendes et al. (2018) demonstrated the accuracy of utilizing CBCT technology to construct a static guide for endodontic access and locating calcified canals. Their study only assessed the ability to achieve access to the canal space.

A more comprehensive study by Zehnder et al. (2016) on the accuracy of guided access using a 3D printed static model for anterior teeth revealed a mean angle deviation of 1.81 degrees with a maximum of 5.6 degree difference. In their study, only maxillary teeth models were utilized in their study. In the present study, both maxillary and mandibular teeth were utilized. In our study, angular deviation in our access for maxillary teeth resulted in 2.01 $\pm$ 1.17 degrees, which is very similar to the results found in the static guide study by Zehnder et al. (2016).

Only one other published study exists by Chong et al. (2019) that use of Navident machine/software (ClaroNav, Toronto, Ontario, Canada) for endodontic access. Unlike our study that measured the accuracy of angular deviation and depth control, their study only analyzed the ability to locate canals; no other analyses were performed.

The dynamic guidance proved to be very accurate in locating canals, but there are limitations that we encountered to the procedure that are worth mentioning. Due to the small access that is created by #1 Munce bur (head diameter of 0.8mm), there was an extreme amount of heat that was created from the frictional contact of the body of the bur to the walls of the access, which can cause the bur to separate in the teeth during drilling. To avoid this, copious irrigation was needed.

The second limitation is the amount of debris that is created during the access by the drill head. Due to the small design of the access, the irrigation did not reach the drill head, which results in an excessive amount of dental debris accumulating at the apical aspect of the access site and as a result, more difficulty was encountered in gaining access to small, constricted canals. This was avoided by not performing continuous drilling during access; it was important to stop midway and clean the flutes of the drill head and irrigate the access prior to continuing.

Positioning became a challenge during accessing of the teeth. In order for the system to work properly, all the sensors must be in view of the overhead of the tracking camera. If any of the sensors, jaw, or handpiece fiducial markers are blocked or are not in view of the tracking camera, the software will automatically pause and the computer monitor will stop tracking the drill path. The software does start tracking again as soon as the tracking fiducials come into view, but this issue made positioning of the handpiece by the operator difficult and assistance positioning during irrigation had to also be modified by irrigating and suctioning in a manner as to avoid blocking the sensors.

There were some limitations to the study design that were encountered. For the File Angular Deviation analysis, a perfect superimposition of the CBCT images was not achieved on some of the models by the software, therefore some of the deviations were slightly over-estimated.

Overall, the X-Guide dynamic system proved to be very accurate in locating canals. The system appears to be more practical in a clinical setting as the plan and completion of the endodontic access can be performed on a patient in one setting. This is contrasted to a static guide system that could require multiple visits due to the extended time it takes to design and print a static guide.

CONCLUSION

The X-Guide dynamic guide system proved to be highly accurate in accessing root canals of anterior teeth while creating a highly conservative access design. The accuracy was consistent among all anterior teeth without any significant difference. The average angular deviation that was achieved on all the accessed teeth was 2.98 $\pm$ 1.57 degrees. All canals were located after the endodontic access was completed using the software. Further research will be needed to study the practicality of the system in a clinical setting. The system had a minimal learning curve of 3 to 4 teeth and promises to be very useful in situations with highly calcified teeth where deep access will be required to locate canals.

FIGURES

Figure 1. Mounted teeth for both upper and lower arches.

Figure 2. Attached X-Guide sensor clip to a lower arch model.

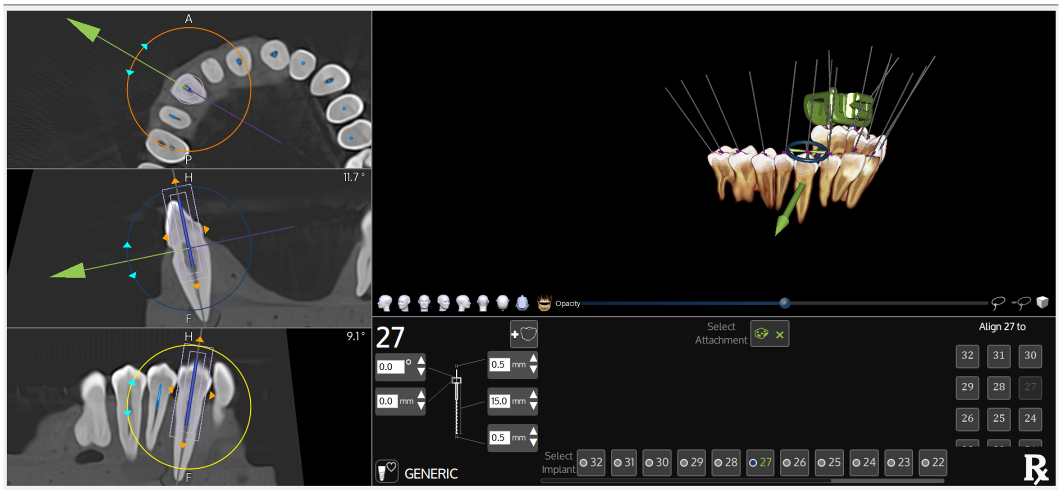

Figure 3. X-Guide system being utilized to place a 15mm x 0.5mm "implant" as a guide to access a maxillary canine.

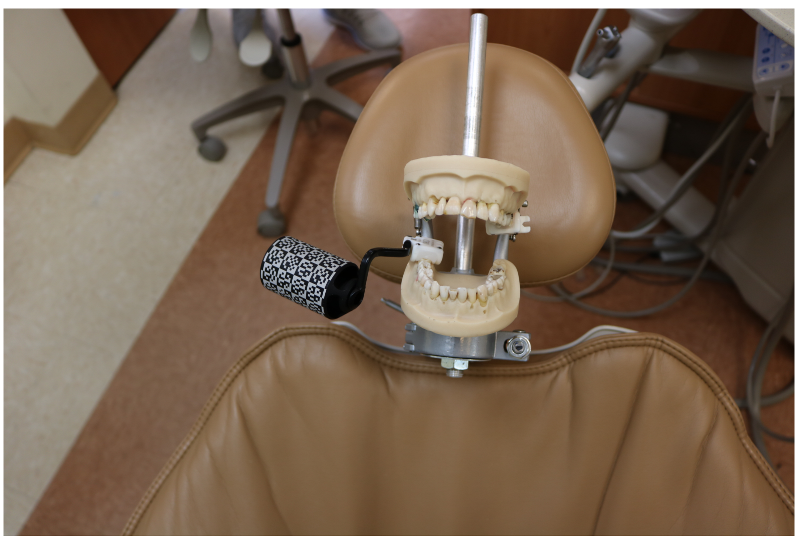

Figure 4. Dentoform mounted to dental operatory chair with attached X-Clip (containing the fiducials) and patient tracker.

Figure 5. Mounted model on a dental operatory chair and X-Guided unit oriented for best visualization by the operator.

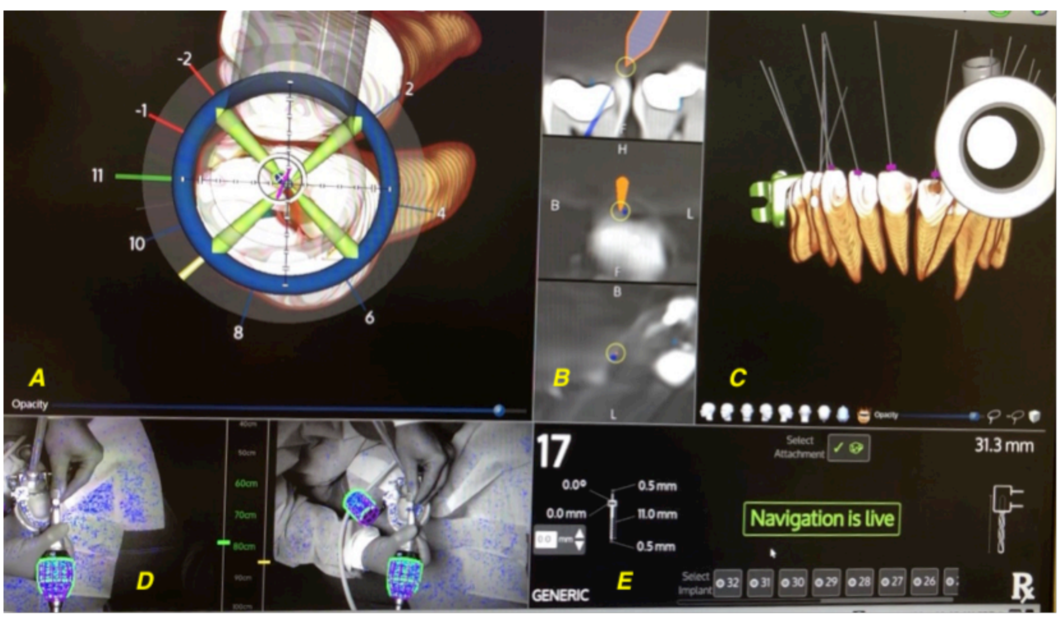

Figure 6. Operator view of the X-Guide monitor during access. *A)* Angulation and target orientation of the bur to the planned implant. *B)* CBCT image

showing the orientation of the burr to the planned design. *C)* Virtual rendition of the teeth and burr angulation. *D)* Overhead camera view monitoring the DFRs. E) Implant information and confirmation of calibration in progress.

Figure 7. Image displaying the Go-plate, Surgical Handpiece and X-Clip with fiducials and attached patient tracker.

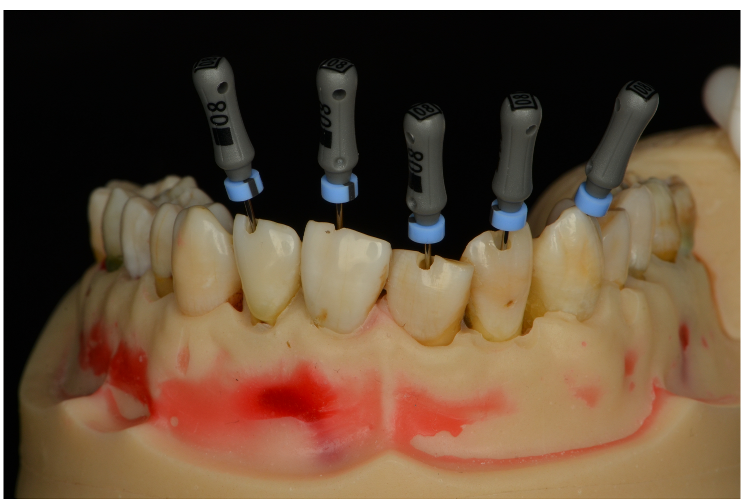

Figure 8. #8 K-files placed passively in the endodontic access holes of upper anterior teeth.

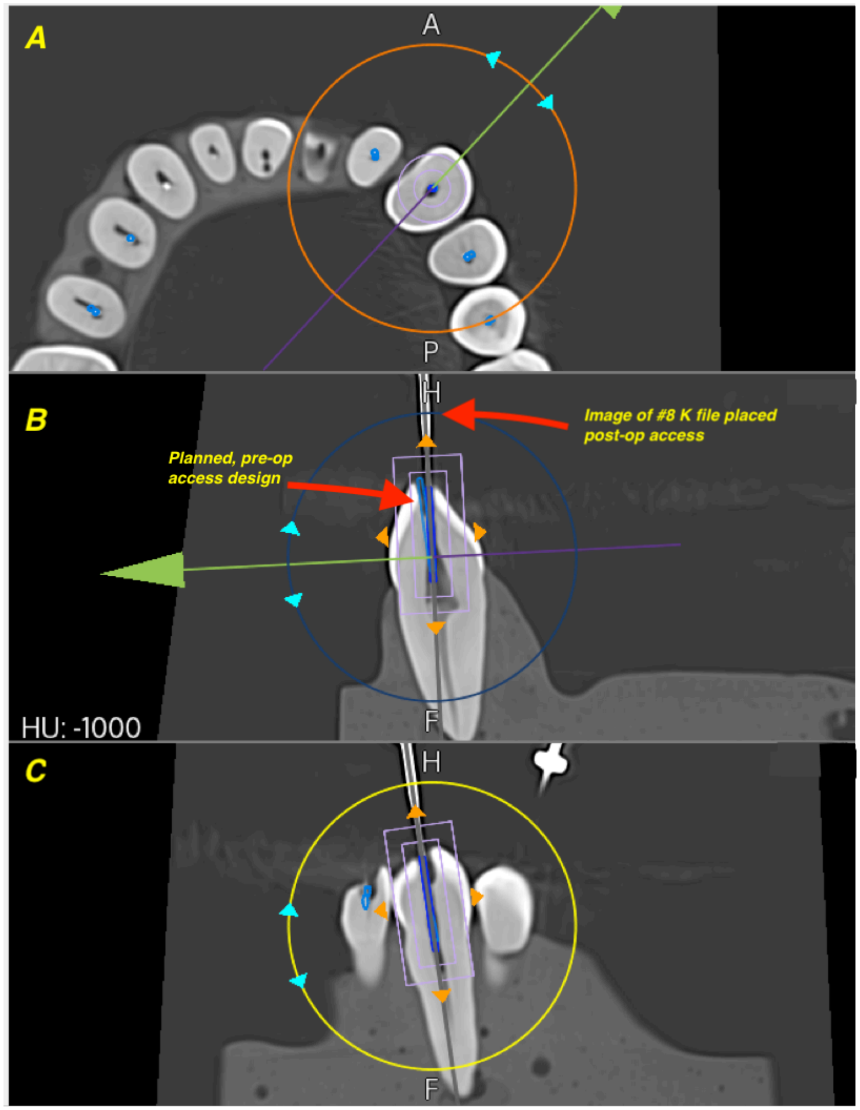

Figure 9. Superimposition of planned access (aqua rectangle) with post-op access (grey K-type file) to evaluate angular deviation. Images A, B, and C are representative of axial, coronal and sagital view of the tooth, respectively.

REFERENCES

1. AAE and AAOMR joint position statement: use of cone beam computed tomography in endodontics 2015 update. Oral Surg Oral Med Oral Pathol Oral Radiol 2015: 120: 508-12.
2. AAE Colleagues of Excellence. Restoration of Endodontically Treated Teeth: The Endodontist's Perspective, Part I. Ammerican Association of Endodontics. 2004.
3. Anderson, J., Wealleans, J., & Ray, J. Endodontic applications of 3D printing. *International Endodontic Journal* 2018.
4. Arisan, V., Karabuda, C., Mumcu, E., & Ozdemir, T. Implant Positioning Errors in Freehand and Computer-aided Placement Methods: a Singel-blind Clinical Comparative Study. *International Journal of Oral & Maxillofacial Implants* 2013: 190-204.
5. Azim AA, Azim KA, Deutsch AS, Huang GT. Acquisition of anatomic parameters concerning molar pulp chamber landmarks using cone-beam computed tomography. J Endod. 2014 Sep;40(9):1298-302.
6. Bahcall JK, Carp S, Miner M, Skidmore L. The causes, prevention, and clinical management of broken endodontic rotary files. Dent Today. 2005 Nov;24(11):74.
7. Block, M., & Emery, R. Static or dynamic navigation for implant placement: choosing the method of guidance. *Journal of Oral & Maxillofacial Surgery* 2016: 269-277.
8. Belograd M. The Genious 2 is coming. Available at: http://www.dentinaltubules.com/ videos/ninja-access-a-new-access-concept-in-endodontics. Accessed September 18, 2016.
9. Benjamin KA, Dowson J. Incidence of two root canals in human mandibular incisor teeth. Oral Surg Oral Med Oral Pathol 1974: Jul;38(1):122-6.
10. Buchanan LS, Maupin C, Khademi J. A preliminary study of the accuracy of dynamic CT-guidance for endodontic access procedures done in 3D printed jaws modeled to have simulated calcified pulp chambers. August 2017. (to be submitted for publication).
11. Buchanan LS. Dynamic CT-Guided Endodontic Access Procedures. Dental Education Laboratories 2018.
12. Buchgreitz, J., Buchgreitz, M., & Bjorndal, L. Guided root canal preparation using cone beam computed tomography and optical surface scans - an observational study of pulp space obliteration and drill path depth in 50 patients. *International Endodontics Journal* 2019; 52(5):559-568.

13. Buchgreitz, J., Buchgreitz, M., Mortensen, D., & Bjorndal, L. Guided Access Cavity Preparation using Cone-beam Computed Tomography and Optical Surface Scans-an ex vivo Study . *International Endodontic Journal* 2016; 790-795.
14. Bystrom, A & Sundqvist, G. Bacteriologic evaluation of the efficacy of mechanical root canal instrumentation in endodontic therapy. *Scandinavian Journal of Dental Research* 1981; 89: 321– 8.
15. Bystrom, A & Sundqvist, G. Bacteriologic evaluation of the effect of 0.5 percent sodium hypochlorite in endodontic therapy. *Oral Surgery, Oral Medicine and Oral Pathology* 1983; 55: 307– 12.
16. Clements RE, Gilboe DB. Labial endodontic access opening for mandibular incisors: endodontic and restorative considerations. J Can Dent Assoc. 1991; 57(7): 587-9.
17. Chong BS, Dhesi M, Makdissi J. Computer-aided dynamic navigation: a novel method for guided endodontics. Quintessence Int. 2019; 50(3): 196-202.
18. Connert, T., Zehnder, M., Amato, M., Weiger, R., Kuhl, S., & Krastl, G. Microguided Endodontics: a method to achieve minimally invasive access cavity preparation and root canal location in mandibular incisors using a novel computer-guided technique. *International Endodontic Journal* 2017; 51(2): 247-255.
19. Di Giacomo GA, Cury PR, de Araujo NS, Sendyk WR, Sendyk CL.Clinical application of stereolithographic surgical guides for implant placement: preliminary results. J Periodontol 2005; 76:503–7.
20. Dalton, BC, Ørstavik, D, Phillips, C, Péttiete, M, Trope, M. Bacterial reduction with nickel–titanium rotary instrumentation. *Journal of Endodontics* 1998; 24:763– 7.
21. Emery, R., Merritt, S., Lank, K., & Gibbs, J. Accuracy of Dynamic Navigation for Dental Implant Placement-Model-Based Evaluation. *Journal of Oral Implantology* 2016; 42(5):399-405.
22. Hoffman, J., Westendorff, C., & Gomez-Roman, G. Accuracy of Navigation-Guided Socket Drilling Before Implant Installation Compared to the Conventional Free-Hand Method in a Synthetic Edentulous Lower Jaw Model. *Clinical Oral Implants Research* 2005; 16(5):609-14.
23. Ingle, JI & Zéldow, BJ. An evaluation of mechanical instrumentation and the negative culture in endodontic therapy. *Journal of the American Dental Association* 1958; 57:471– 6.
24. Kakehashi S, Stanley HR, Fitzgerald RJ. The Effects of Surgical Exposures of Dental Pulps in Germ-Free and Conventional Laboratory

Rats. Oral Surg Oral Med Oral Pathol. 1965 Sep;20:340-9.
25. Kim GB, Lee S, Kim H. Three-dimensional print- ing: basic principles and applications in medicine and Radiology. Korean Journal of Radiology 2016; 17:182–97.
26. Klein, M., & Abrams, M. Computer-guided surgery utilizing a computer-milled surgical template. *Practical Procedures & Aesthetic Dentistry* 2001; 13(2):165-9.
27. Lara-Mendes, S., Barbosa, C., Santa-Rosa, C., & Machado, V. Guided Endodontic Access in Maxillary Molars Using Cone-beam Computed Tomography and Computer-aided Design/Computer-aided Manufacturing System: A Case Report. *Journal of Endodontics* 2018; 44(5):875-879.
28. LaTurno SA, Zillich RM. Straight-line endodontic access to anterior teeth. Oral Surg Oral Med Oral Pathol. 1985; 59(4):418-9.
29. Linn J, Messer HH. Effect of restorative procedures on the strength of endodontically treated molars. J Endod 1994; 20(10):479–85.
30. Ludlow JB, Lester WS, See M, Bailey LJ, Hershey HG. Accuracy of measurements of mandibular anatomy in cone beam computed tomography images. Oral Surg Oral Med Oral Path Oral Radiol Endod 2007;103:534-42.
31. Madjar D, Kusner W, Shifman A. The labial endodontic access: a rational treatment approach in anterior teeth. J Prosthet Dent. 1989; 61(3):317-20.
32. Mannan G, Smallwood ER, Gulabivala K. Effect of access cavity location and design on degree and distribution of instrumented root canal surface in maxillary anterior teeth. Int Endod J 2001; 34:176–183.
33. Mauger MJ, Waite RM, Alexander JB, Schindler WG. Ideal endodontic access in mandibular incisors. J Endod. 1999; 25(3):206-7.
34. Mena-Alvarez, J., Rico-Romano, C., Lobo-Galindo, A., & Zubizarreta-Macho, A. Endodontic treatment of dens evaginatus by performing a splint guided access cavity. *Journal of Esthetic and Restorative Dentistry* 2017; 12;29(6):396-402.
35. Mischkowsk RA, Zinser MJ, Neugebauer J, Ku¨bler AC, Zo¨ller JE. Comparison of static and dynamic computer-assisted guidance methods in implantology. Int J Comput Dent. 2006;9:23–35.
36. Nattress BR, Martin DM. Predictability of radiographic diagnosis of variations in root canal anatomy in mandibular incisor and premolar teeth, In Endod J 1991; 24(2):58
37. Nayak, A., Jain, P., Kankar, P., & Jain, N. Computer-aided design-based guided endodontic: A novel approach for root canal access cavity

preparation. *Proceedings of the Institution of Mechanical Engineers, Part H* 2018; 232(8):787-795.
38. Nickenig, H., Wichman, M., Hame, J., Schlegel, K., & Eitner, S. Evaluation of the Difference in Accuracy Between Implant Placement by Virtual Planning Data and Surgical Guide Templates versus the Conventional Freehand Method - a Combined in vivo-in vitro Technique using Cone-Beam CT (part II). *Journal of Craniomaxillofacial Surgery* 2010; 38(7):488-93.
39. Pinskey, H., Champleboux, G., & Sarment, D. Periapical Surgery using CAD/CAM Guidance: Preclinical Results. *Journal of Endodontics* 2007; 33(2):148-51.
40. Ramirez-Sebastià A, Bortolotto T, Cattani-Lorente M, Giner L, Roig M, Krejci I. Adhesive restoration of anterior endodontically treated teeth: influence of post length on fracture strength. Clin Oral Investig 2014;18(2):545–54
41. Robinson D, Goerig AC, Neaverth EJ. Endodontic access: an update, Part I. Compendium. 1989; 10(5):290-2, 294-6, 298
42. Robinson D, Goerig AC, Neaverth EJ. Endodontic access: an update, Part II. Compendium. 1989; 10(6):328-30, 332-3.
43. Sarment, D., Pedrag, S., & Clinthorne, M. Accuracy of Implant Placement with a Stereolithographic Surgical Guide. *The International Journal of Oral & Maxillofacial Implants* 2003; 18(4):571-7.
44. Scarfe WC, Levin MD, Gane D, Farman AG. Use of cone beam computed tomography in endodontics. Int J Dent 2009:1-20.
45. Strateman SA, Huang JC, Maki K, Miller AJ, Hatcher DC. Comparison of cone beam computed tomography imaging with physical measures. Dentomaxillofac Rad 2008;37:80-93.
46. Torres, A., Shaheen, E., Lambrechts, P., Politis, C., & Jacobs, R. Microguided Endodontics: a case report of a maxillary lateral incisor with pulp canal obliteration and apical periodontitis. *International Endodontic Journal* 2019 Apr;52(4):540-549.
47. Vertucci F. Root canal anatomy of the human permanent teeth. Oral Surg Oral Med Oral Pathol Oral Radio Endod 1984; 58:58.
48. Widmann, G., Stoffner, R., Schullian, P., Widmann, R., Keiler, M., Zangerl, A., Puelacher, W., Bale, R. J. Comparison of the accuracy of invasive and noninvasive registration methods for image-guided oral implant surgery. Int J Oral Maxillofac Implants. 2010; 25(3):491-8
49. Zhang Y, Liu Y, She Y, Liang Y, Xu F, Fang C. The Effect of Endodontic Access Cavities on Fracture Resistance of First Maxillary Molar Using the Extended Finite Element Method. J Endod. 2019; 45(3):316-321

50. Zehnder, M., Connert, T., Weiger, R., Krastl, G., & Kuhl, S. Guided Endodontics: Accuracy of a Novel Method for Guided Access Cavity Preparation and Root Canal Location. *International Endodontic Journal* 2016; 49(10):966-72.