Anatomic Investigation of the Roots of Second Mandibular Molars using Micro CT

A THESIS
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA
BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

Advisor: Dr. Scott McClanahan

August 2011

Acknowledgements

This research was supported in part by the Minnesota Dental Research Center for Biomaterials and Biomechanics and NIH/NIDCR grant number DE09737. Thank you to Dr. Alex Fok, Mario Pintado, and the staff for technical assistance and support.

Dr. McClanahan, Dr. Bowles, and Dr. Fok; thank you for acting as my advisors during this project and for editing advice.

Dr. McClanahan, Dr. Bowles, and Dr. Baisden; your support related to the research project as well as all aspects of the program has been much appreciated!

Staff of the VAMC, Minneapolis; thank you for your help in collecting teeth.

Dr. Samantha Harris; thank you for sharing helpful hints and making the process much more enjoyable.

Dedication

This project is dedicated to my support team at home. My husband, Brian Barsness, and our children, Erik and Eva. Thank you for keeping me on track, being patient, and distracting me when I needed it.

Abstract

An understanding of tooth anatomy is an important cornerstone in providing successful endodontic treatment. Detailed images of tooth anatomy using microcomputed tomography allow measurements of pulpal floor anatomy, canal configurations, canal dinemsions, root wall thickness, presence of calcifications, and apical anatomy. The aim of this study of eighteen mandibular second molars using micro CT was to investigate various aspects of tooth anatomy. The most frequently found mesial root canal configuration was Vertucci Type 7 (1-2-1-2) in 33% of samples. Distal canals were most frequently Vertucci Type 1(1), with 61% of samples showing this configuration. 11% of samples had two canals, 44% of samples had three canals, 33% of samples had four canals, and 11% of samples had five canals at some point along the root. On average, root wall thickness between the mesiobuccal root and the furcation was the thinnest at 1.23 mm. The mesiolingual canal root wall thickness was on average 1.29 mm, and the distal was 1.41 mm. 78% of samples had calcifications present in both the pulp chamber and within the canals; 17% of samples were free from calcification in both the pulp chamber and within the canals; one (6%) sample had calcification in the chamber only. Other reported data included canal dimensions at one millimeter increments along the root, pulpal floor anatomy, and apical anatomy.

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INTRODUCTION

The main goal of endodontic therapy is to prevent or treat apical periodontitis. This goal is accomplished in the root canal system by cleaning, shaping, and disinfection, which allows for three-dimensional obturation of the canals and associated structures (Schilder 1967, 1974). However, the complexity of the root canal anatomy can create challenges for the clinician seeking to accomplish these objectives (Peters, 2004). A thorough understanding of canal anatomy is an essential first step toward implementation of an effective cleaning, shaping, and disinfection strategy.

The morphologic study of canals in teeth has more than a hundred year history and has been accomplished in many different ways. Even in early studies, such as Hess in 1925, a wide variation and complexity of root canal systems was reported (Hess, 1925). Early reports on canal morphology were made from direct observations of specimens with the naked eye or the light microscope. As the complexity of these small subjects became apparent, investigators sectioned teeth and looked at the intricacies with microscopes. Techniques which utilized injection of material into canals with subsequent decalcification of the tooth structure provided a way to see canals and their relationships to each other without as much modification to the specimens. Radiographic techniques have also been utilized with and without files in canals as a less invasive way to visualize canals, but have the disadvantage of a two dimensional image of a three dimensional structure which can result in missing canal anatomy. Conventional computed tomography provided a non-invasive three-dimensional image of teeth, but with a section thickness of 1.5 millimeters, the reproductions lacked some detail (Gambill et al., 1996).

More recently, microcomputed tomography (micro CT) has given investigators looking at canal systems *in vitro* an exceptionally detailed three-dimensional image that can be obtained without any modification to the tooth (Nielson et al., 1995; Dowker et al., 1997). This image allows for visualization of canals and their interconnections and led to studies of canal curvature (Lee et al., 2006), volume of canals (Peters et al., 2000; Rhodes et al., 1999), and canal anatomy (Plotino et al., 2006). Several investigators have used micro CT to evaluate the effect that instrumentation has on the canal system with pre and post-instrumentation scans (Bergmans et al., 2001; Peters et al., 2001; Peters et al., 2001; Peters et al., 2003). Micro CT has voxel sizes determined by pixel and slice spacing. A micro CT unit can produce sections spaced 127 µm with pixel resolution of 127 µm, which corresponds to a cubic voxel measuring 127 µm/side (Nielson et al., 1995). Along with the canal configuration and volume of the canals which have been studied extensively using micro CT, the detail of the micro CT images would allow for study of pulp floor morphology, measurement of thickness of root walls and diameters of canals, presence of calcifications within canals and the pulp chamber, as well as areas of exit of major and accessory foramina.

The purpose of this study was to describe the morphology of heavily restored mature mandibular second molars via micro CT and compare findings to those of previous studies that utilized other methods to study various aspects of anatomy. Teeth were collected locally and had been previously restored, which makes them representative of teeth that are seen clinically in need of root canal treatment. Specifically, this study evaluated: pulp floor anatomy, canal configuration, canal diameter from mesial to distal and buccal to lingual every millimeter along the root, root wall thickness every millimeter from each canal to the furcation, presence of calcifications in the pulp chamber and in the canal space, and apical anatomy.

REVIEW OF THE LITERATURE

Second mandibular molars were thought to have the same canal anatomy as first mandibular molars in early studies, perhaps in part because specimens were grouped together. As investigators began to identify the teeth and look at them separately, differences in morphology became apparent. In second mandibular molars, an understanding of canal morphology as it relates to nonsurgical root canal therapy is of particular importance as surgical intervention in the area of the second mandibular molar is not always feasible and can be difficult due to proximity of roots to nerves, thickness of the cortical plate, and surgical access.

Canal Classification

Several canal classification systems exist to describe canal configurations. Weine described three types of canal configurations in 1969, later adding a fourth in 1976. Type 1 (1) describes a single canal from the pulp chamber to the apical foramen; type 2 (2-1) had two canals at the chamber which merged into one at the apical exit; type 3 (2-2) systems had two canals the entire length of the root; type 4 (1-2) had one canal at the coronal portion which divides into two and exits as two (Weine 1969, 1976). Vertucci expanded the categories into eight, with the following definitions: type 1 (1) a single canal from the chamber to the apical foramen, type 2 (2-1) two canals leave the chamber and merge into one, type 3 (1-2-1) one canal leaves the chamber, divides into two, and rejoin again to exit the foramen, type 4 (2) two separate canals leave the chamber and exit the foramen, type 5 (1-2) one canal leaves the chamber and divides into two which exit from two foramina, type 6 (2-1-2) two canals leave the chamber, merge into one, and divide again into two, type 7 (1-2-1-2) one canal leaves the chamber, divides into two, which merge into one, and then divide into two and exit separate foramina, and type 8 (3) three separate canals exist from chamber to foramina (Vertucci 1974, 1984). In a study of mandibular molars in a Burmese population, seven additional canal configurations were described. These supplemental canal configurations included: type 9 (3-1) with three canals merging to one, type 10 (3-2) with three canals converging to two, type 11 (2-3) with two canals expanding to three, type 12 (2-1-2-1) which starts as two, combines, splits again, and finally finishes united, type 13 (4-2) with four canals leaving the chamber becoming two prior to their exit, type 14 (4) with four canals for the entire root length, and type 15 (5-4) with five canals exiting the chamber and four eventually exiting the root apex (Gulavibala et al., 2001). In 2004, two additional canal configurations were described including a 1-3 relationship (Type 16) and a 1-2-3-2 canal system (Type 17) (Sert et al., 2004). Other canal classifications have been described in the literature; however, in this study, canal configurations described by Vertucci, Gulavibala, or Sert were used to describe the canal relationships found. A systematic review study of mandibular first molars included an excellent summary of root configurations reported in the literature (de Pablo et al., 2010), which is represented by

Figure 1.

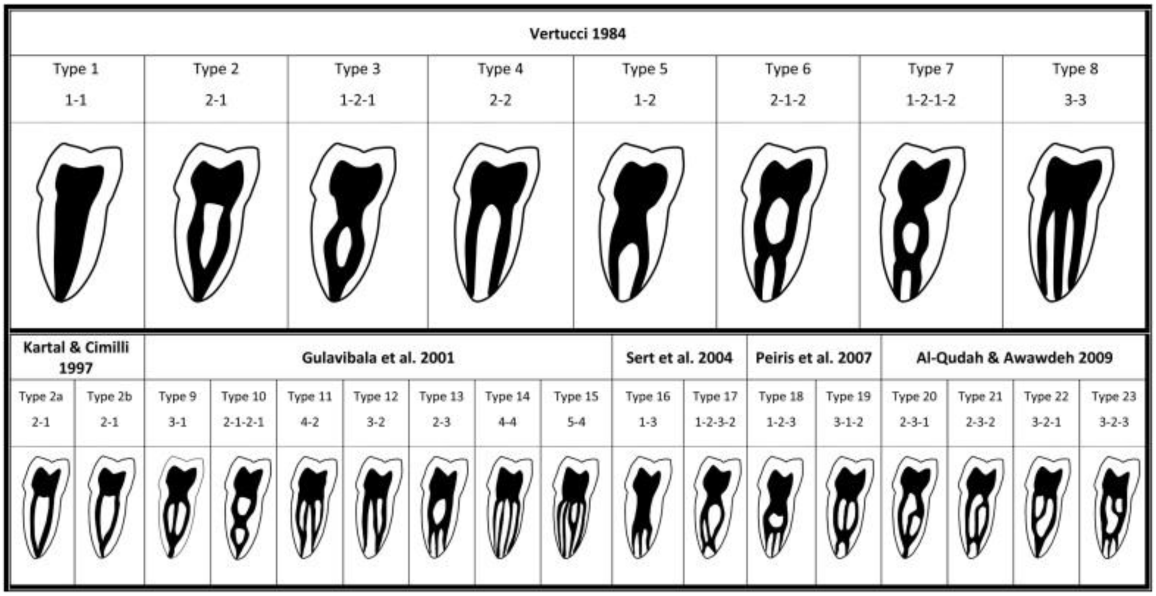


Figure 1: Summary of root canal configurations reported in the literature (de Pablo et al., 2010)

Number of Canals

Many investigators have described number of canals in each root and canal configuration. In a radiographic study of 259 extracted second mandibular molars, 5.6% of teeth were found to have four canals (Pineda & Kuttler, 1972). In an examination of 100 distal roots of mandibular second molars, 5% were Weine type 2 and 3% were Weine type 3, resulting in a total of 8% with four canals (Green 1973). A retrospective clinical *in vivo* radiographic study of 416 second mandibular molars found 1 canal 1% of the time, 2 canals 4.1% of the time, 3 canals 89.4% of the time, and 4 canals 5.5% of the time (Hartwell & Bellizzi, 1982). In an *in vitro* study of 75 extracted mandibular second molars with files placed at working length, canal configuration was described in the mesial and distal root. The mesial root findings included: 1) Weine type 1 configuration 4% of the time, 2) type 2 configuration 52% of the time, and 3) type 3 configuration 40% of the time. The distal root findings included: 1) Weine type 1 configuration 85.3% of the time, 2) type 2 9.3%, and 3) type 3 1.3%. Overall, four canals were found in 10.7% of the teeth studied. The remaining 4% of samples were either teeth that contained only one canal total or were C-shaped systems. (Weine & Pasiewicz, 1988).

Canal Isthmuses

An isthmus is a narrow, ribbon-shaped communication between canals that contains pulp tissue (Weller et al., 1995). This communication can vary in terms of size and shape. The irregular nature of an isthmus can make it difficult to access with endodontic instruments and may represent a potential reservoir for bacteria (Teixeira et al., 2003). Any root with two canals can exhibit isthmus communications. Mesial roots of mandibular molars have been shown to frequently harbor communicating canals, reported more frequently in first mandibular molars due to more frequent studies on these teeth (Hsu & Kim 1997; Skidmore & Bjorndal 1971; Teixeira et al., 2003; Vertucci, 1984). In a micro computed tomography study of the apical five millimeters of twenty mandibular first molars, the percentage of sections showing isthmuses ranged from 17.25% to 50.25% (Mannocci et al., 2005). In this microcomputed tomography study, the communications between canals were recorded at each millimeter down the root and isthmuses were seen in terms of canal complexities.

Root Morphology

Gulavibala classified root morphology of mandibular molars in six different groups: 1) three separate roots, 2) two separate roots with both roots flat mesiodistally, 3) two separate roots with mesial root flat mesio-distally and distal root conical, 4) two fused roots, for more than half their length with buccal and lingual grooves between the roots, 5) single conical root, and 6) C-shaped root, a single root with a cross-sectional ‘C-shape’ (Gulavibala et al., 2001).   In this study, roots were classified as described by Gulabivala and colleagues.

Pulp Floor Anatomy

Knowledge of pulp floor anatomy is essential for successful access of the root system. In a study of extracted mandibular molars including those with restorations or caries, the distance from buccal cusp to pulp chamber ceiling was 6.36 ± 0.93 mm, the pulp chamber height was 1.57 ± 0.68 mm, and the distance from the pulp chamber floor to the furcation was 2.96 ± 0.78 mm (Deutsch & Musikant, 2004). In calcified and heavily restored teeth, location of canal orifices were studied in order to make access a more predictable process. The law of symmetry described the location of canals in mandibular molars as equidistant from a line dividing a molar mesiodistally. Canals were found at the junction of the walls and the floor at the terminus of root development fusion lines (Krasner & Rankow, 2004). In the study by Krasner and Rankow, the distance between the canal orifices was not reported. The distances between the mesial canals and from the mesial to distal canals may be a helpful guideline during access, especially in heavily restored and calcified teeth. These are among the measurements taken in this study.

Root Wall Thickness

The flared preparation obtained in root canal instrumentation permits effective cleaning of the canal system and facilitates obturation (Schilder, 1967). With the advent of flared preparations for filling with gutta-percha, it was recommended to use anticurvature filing to direct the preparation away from the thinner portions or danger zones of the root structure in the furcation area of mandibular molars (Abou-Rass et al., 1980). The area of the root in first mandibular molars that has been thought to be the most vulnerable to thinning of root structure or strip perforation was described as 1.5 mm below the furcation in the mesial root. This area of dentin and cementum was 1.2-1.3 mm thick prior to preparation, and was less thick than it appears radiographically by a fifth (Berutti & Fedon, 1992). It seems reasonable to assume that mandibular second molars would also have a danger zone of thinner dentin and cementum, but this measurement has not been reported. In this study, measurements of root wall thickness from canal to the furcation were taken in both the mesial and distal roots in millimeter increments along the length of the root.

Calcifications

The presence of calcifications in the pulp chamber and within the canals can complicate root canal access and instrumentation. Calcification of pulp tissue is thought to be a common occurrence, but etiology is not well understood. In the coronal area, pulp calcifications typically take the form of discrete, concentric pulp stones. Calcification tends to be more diffuse in the radicular pulp (Trowbridge et al., 1996). In mature teeth that have been subjected to wear, caries, or restoration, hard tissue apposition along the root canal walls appears to be a slow, normally occurring process. Calcification can be accelerated in circumstances of trauma, autotransplantation, and orthodontics (Robertson et al., 1996). In an *in vitro* study of 36 extracted teeth comparing radiographs to histologic sections, calcifications were seen within the canal in 27% of the sectioned specimens. In no histologic section was the canal diameter smaller than the tip of a #10 endodontic file (<0.1mm), though it is possible that calcifications could constitute a barrier to the passage of even the smallest instruments (Kuyk, 1990). In this study, presence or absence of calcifications was recorded both for the pulp chamber and for the canals.

Apical Anatomy

In the apical aspect of the tooth, clinically significant anatomic features include the apical foramen and lateral, secondary, and accessory canals. The presence of accessory, secondary, and lateral canals are most common in the apical region, with 17% of 27.4% total ramifications (communications with the periodontium other than the apical foramen) found apically (DeDeus, 1975). DeDeus defines a lateral canal as extending from the main canal to the periodontal ligament, with an inclination from perpendicular to one that tends toward the apex. The secondary canal extends from the main canal to the periodontal ligament in the apical region, while the accessory canal is derived from the secondary canal branching off to the periodontal ligament. When multiple foramina are present, the largest one is referred to as the apical foramen and the smaller ones as accessory canals. Another study describing accessory canals found that 73.5% occurred in the apical third of the root, 11.4% in the middle third, and 15.1% in the cervical third of roots (Vertucci 1984). During root formation, the apical foramen is usually located at the anatomic apex. As the tooth matures, the apical foramen is found a short distance (18-25 year olds 0.495 mm) coronal to the anatomic apex of the root. This distance increases with aging (55+ year olds 0.607 mm) as cementum is added apically (Kuttler, 1955). Another investigator found that 92% of major foramina deviated from the anatomic apex by 0.59 mm as measured from the most coronal point of the foramen (Burch & Hulen, 1972). In an *in vitro* sectioning study of extracted teeth (average age: 48.9 years), the distance from the major foramen to the constriction or cementodentinal junction was on average 0.72 mm, and the width of the constriction was 0.189 mm which is nearly the size of a 20 file (Stein & Corcoran, 1990).

METHODS AND MATERIALS

This project was exempted from review by the Institutional Review Board of the University of Minnesota. This research was supported in part by the Minnesota Dental Research Center for Biomaterials and Biomechanics by allowing use of the micro CT and reconstruction and viewing software, as well as providing technical support. Extracted teeth were collected between 9/2009 and 11/2010 from the Oral Surgery department of the Veteran's Administration Medical Center of Minneapolis, Minnesota. The teeth were stored in 0.02% sodium azide in 0.9% saline at room temperature. If caries were present at a depth that would include the pulp chamber or canal, they were excluded. Any teeth with roots that were not intact were excluded. Using the classification of root morphology proposed by Gulabivala, teeth designated group 6 or C-shaped were not included in potential specimens; groups 1-5 were included. A panel of three experts included two faculty for a dental school tooth morphology curriculum and one board certified endodontist. Teeth with restorations other than full coverage crowns, which could mask the identity of the tooth, were included. The panel identified teeth as second molars, with teeth being included in the sample only if all three panelists agreed upon the designation of second mandibular molar.

Twenty five teeth meeting the above criteria were prepared for micro CT scan. Preparation included removal of tissue and adhered bone from tooth roots by hand scaling and rinsing the roots with saline. For each tooth, an index or mounting jig (Figure 2) was made to attach to the mount of the micro CT unit using Integrity ® (3M, Maplewood, MN) temporary crown and bridge material. The coronal aspect of the tooth was placed into the material with root ends pointing upward. Wax was placed on the occlusal aspect of the tooth crown for later visualization of the coronal anatomy and restoration. The index had two cylindrical metal posts which the acrylic resin closely approximated allowing the index to be placed in a reproducible way and to reduce chance of movement of the sample.

Figure 2: Mounting jig, access to the occlusal aspect of sample, and the sample mounted in the jig.

Micro computed tomography scans were taken of each sample using the XTEK XT H 225 micro CT (Metris, Nikon Metrology NV, Leuven, Belgium) (Figure 3 & 4). CT Pro software (Nikon Metrology NV, Leuven, Belgium) was used to reconstruct the images. By examining the reconstructed images of the teeth using the VG Studio software (Vision Graphics Studio, Heidelberg, Germany) (Figure 5), measurements of the specimens could be taken. Measurements of the pulp floor anatomy, root wall thickness, canal diameter in a mesiobuccal and distolingual direction, and aspects of apical anatomy were taken. Presence or absence of calcifications in the pulp chamber and within canals were recorded. Images were rendered translucent as compared to the canals for determining canal types and classifying the root morphology per the Vertucci, Gulavibala, or Sert classification systems.

Figure 3: The Metris XTEK XT H 225 Micro CT Unit, MDRCBB

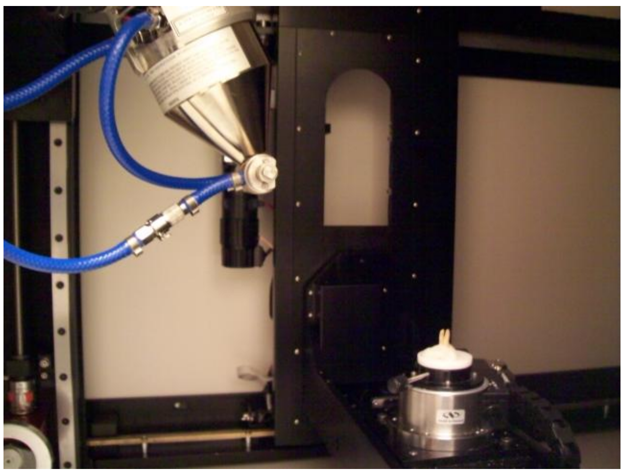


Figure 4: View of the sample in place on the platform and secured with a screw bolt

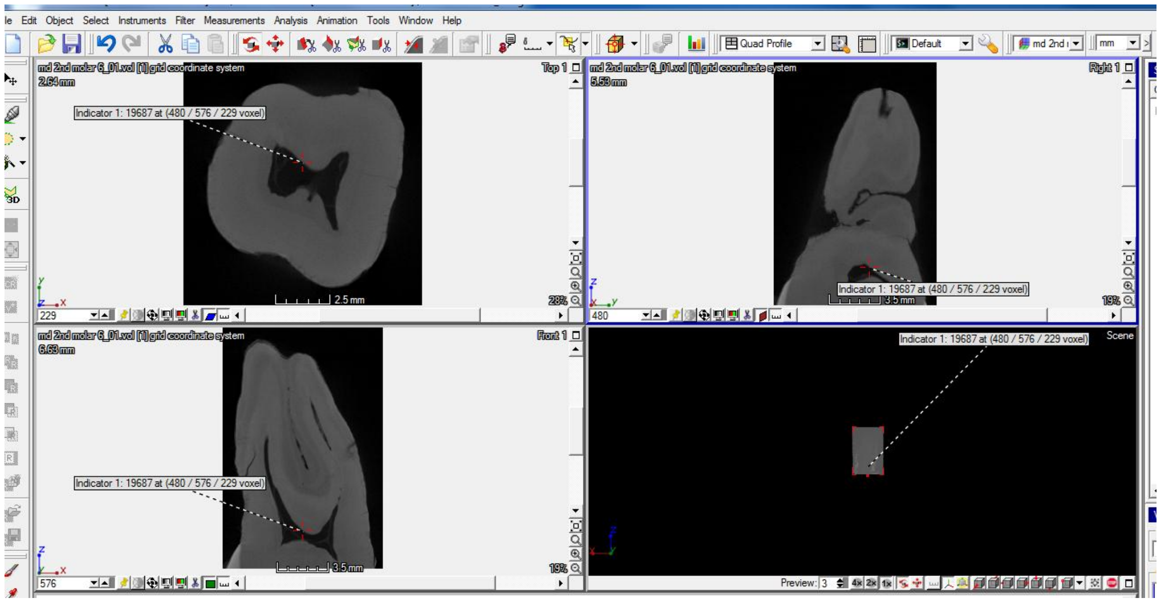
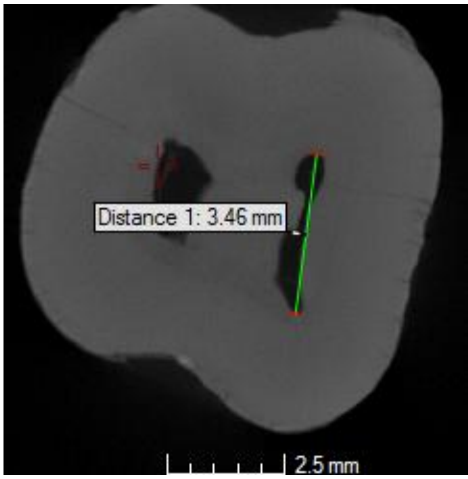


Figure 5: Processing a sample using VG Studio software

In the pulpal floor area, the following measurements were taken from 0.5 millimeters below the coronal-most point of the pulpal floor: 1) distance between outermost aspect of mesial canal(s) (Figure 6), 2) distance between outermost aspect of distal canal(s) (Figure 7), 3) distance from the mesial aspect of mesial canals to the distal aspect of distal canal(s) along the midline of the tooth (Figure 8), 4) buccolingual and mesiodistal measurements of each canal orifice, and 5) presence of calcifications in pulp chamber and in canals (Figure 9). For the measurement from the pulpal floor to the furcation, the distance from the most coronal aspect of the pulpal floor to the most coronal aspect of the furcation was used (Figure 10). The reference point of 0.5 millimeters below the coronal-most aspect of the pulpal floor used for most data in this study allowing observation of the canal orifices at the point one would see them clinically. From this reference point, measurements along the root in one millimeter increments would be similar to the way a clinician works in non-surgical root canal treatments.



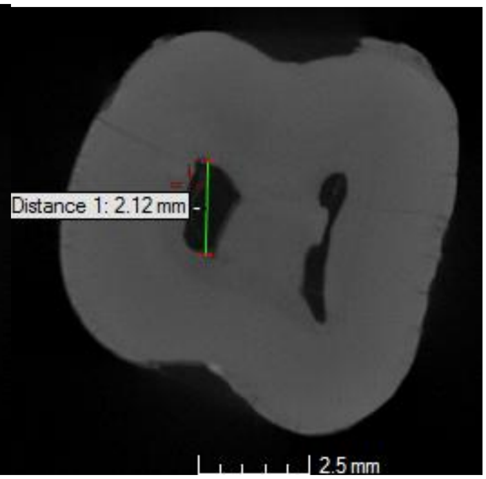
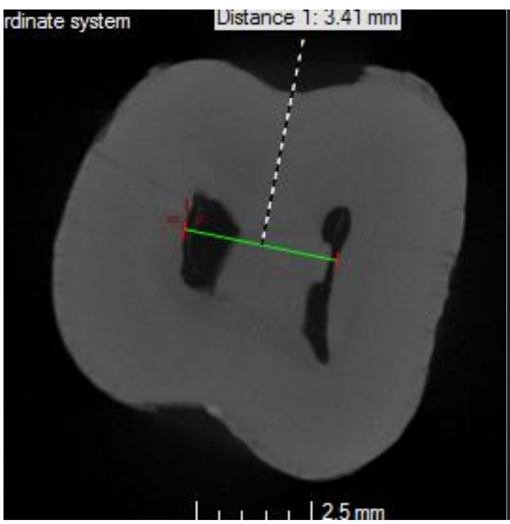


Figure 6: Buccolingual dimension of the mesial orifices

Figure 7: Buccolingual dimension of the distal orifice



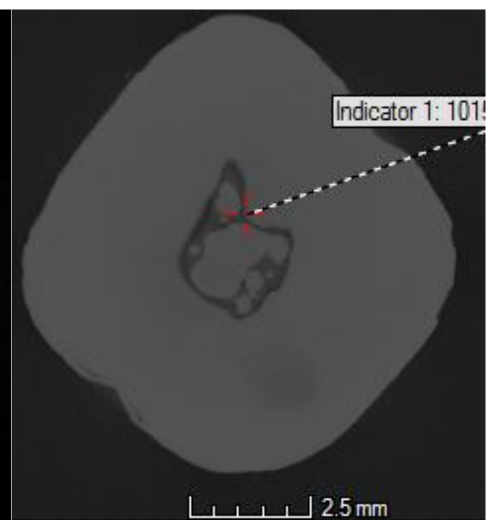


Figure 8: Distance from mesial aspect of mesial orifice to distal aspect of distal orifice at the midline of the tooth

Figure 9: Presence of calcifications within the pulp chamber

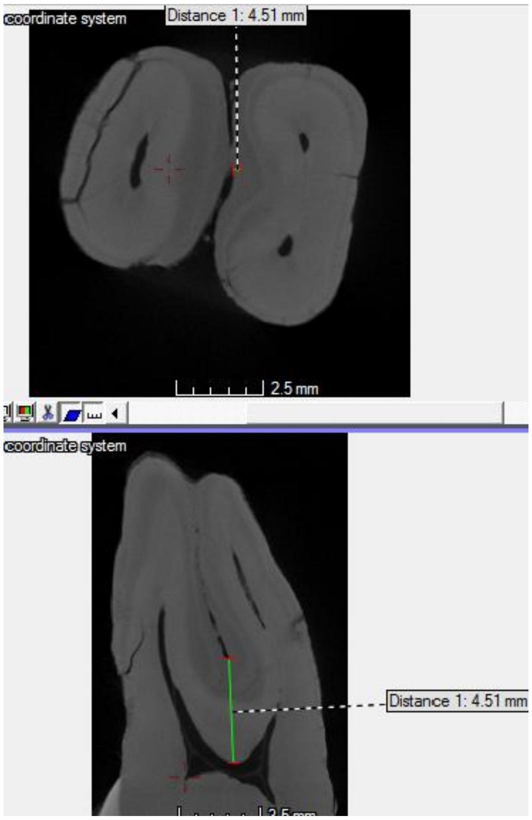
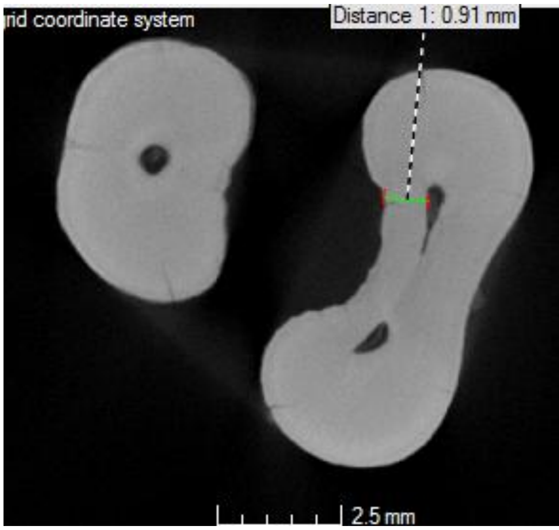


Figure 10: Distance from pulp floor to furcation

Root length was measured from 0.5 mm below the coronal-most point of the pulpal floor to the anatomic apex. Every one millimeter from the coronal reference of 0.5 millimeters from the coronal-most point of the pulpal floor, measurements of the canals were taken in a mesiodistal and buccolingual dimension. The thinnest area of the root canal wall from each canal was measured at each millimeter increment as well (Figure 11 & 12).



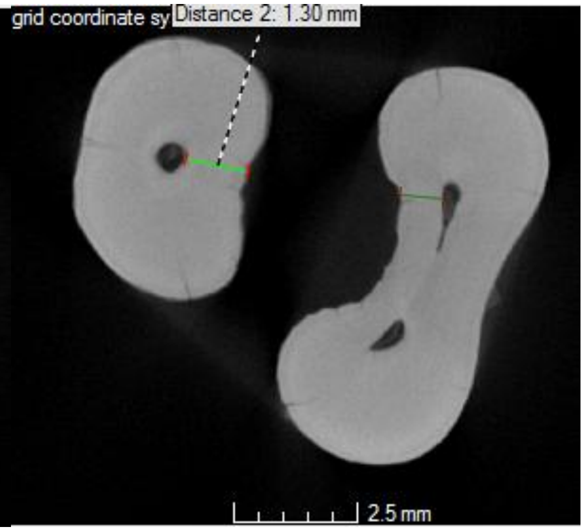


Figure 11: Distance from mesiobuccal canal to the furcation

Figure 12: Distance from distal canal to the furcation

In the apical area of the tooth, the following were recorded: 1) number of major foramina in each root corresponding to the main canal(s), 2) number of accessory foramina, 3) distance from the most coronal aspect of the major foramen to the anatomic apex (Figure 13), 4) distance from the minor constriction to the major foramen, and 5) smallest width of the minor constriction.

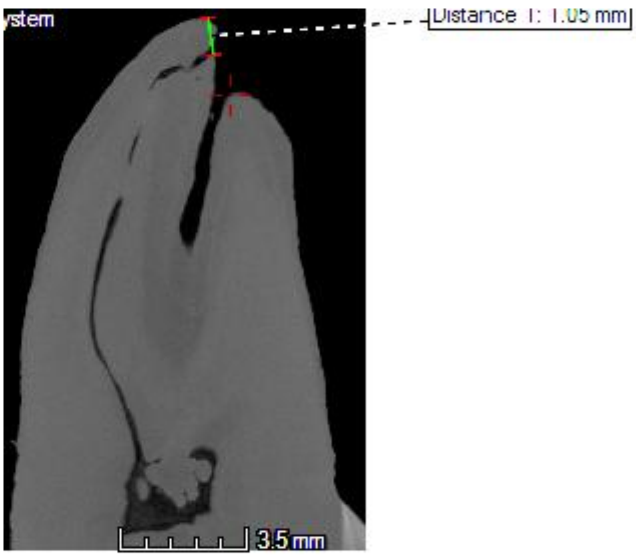


Figure 13: Distance from coronal aspect of major foramen to the anatomic apex

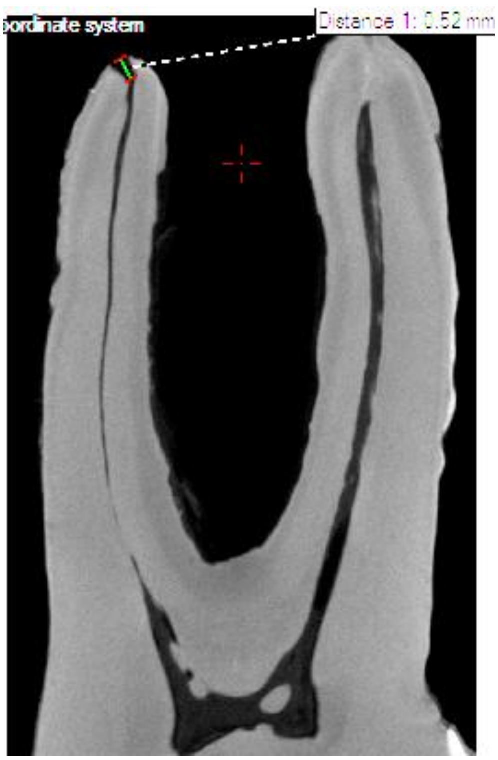


Figure 14: Distance from the cementodentinal junction to the major foramen

Figure 15: Smallest width of the minor constriction

In order to determine the canal configurations for the samples, the images were rendered translucent using the VG Studio Max 2.0 software, allowing for observation of canal complexities (Figures 16-18). Using the software, the image can be rotated and seen from any view desired. The translucent images were also helpful in identification of major foramina.

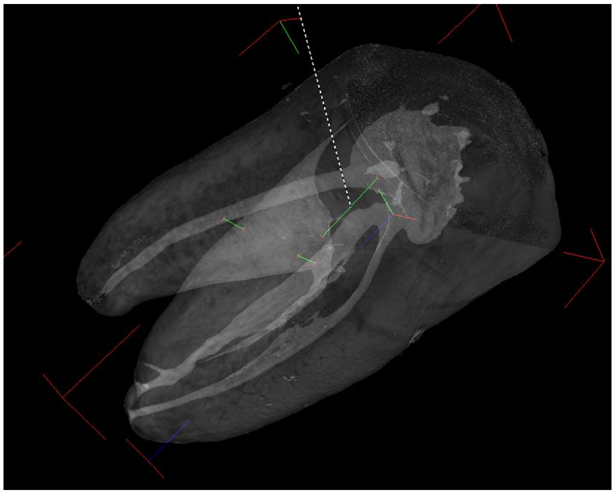


Figure 16: Micro CT image of a second mandibular molar rendered translucent using VG Studio Max 2.0 software

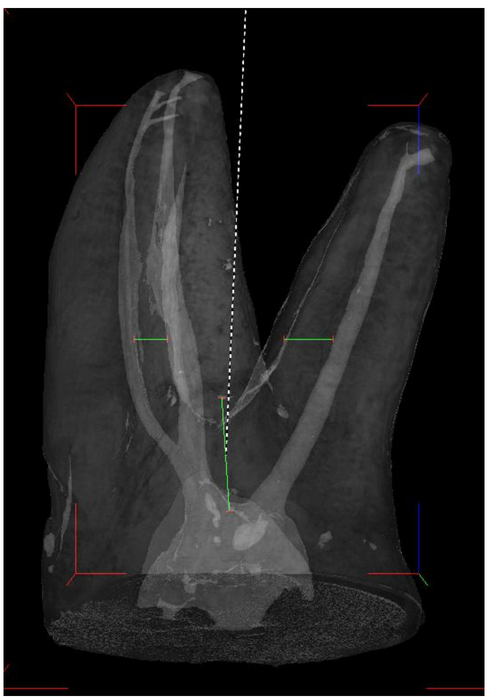


Figure 17: Micro CT image of a second mandibular molar

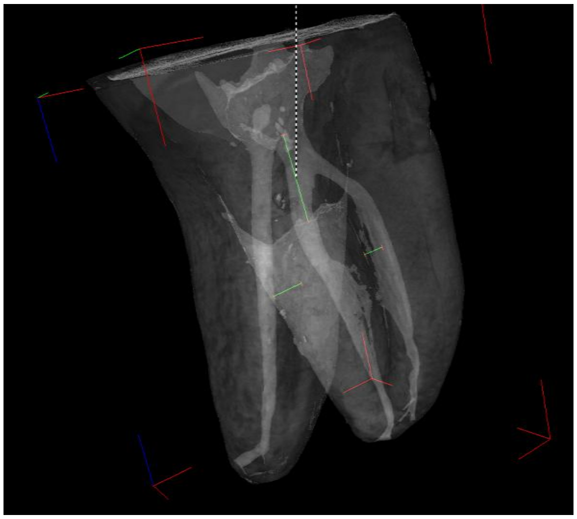


Figure 18: Micro CT image of a second mandibular molar

In order to check the accuracy of the micro CT measurements on the imaging software, measurements were calibrated using digital calipers (S-T Industries, St. James, MN) which are accurate to 0.01 millimeter. The diameter of the shank of a #2 Gates Glidden bur (Dentsply International, York, PA) at a point 4.0 millimeters from the tip and the shank of a 0.7 millimeter PREPI bur (Dentsply International, York, PA) were measured with the digital calipers. The Gates Glidden and PREPI burs were then scanned, reconstructed, and measured using the VG Studio Max 2.0 software at the same points. This revealed that the distances measured on the micro CT images were accurate to 0.025 millimeters, an error that was not considered to be clinically significant.

According to the VG Studio Max 2.0 software properties, the resolution of the x-axis was 0.01220 mm, the y-axis was 0.01220 mm, and the z-axis was 0.01220 mm. The total voxel count in an average tooth scan was 1344938505. An average tooth scan has the dimensions of 11.41 millimeters by 12.21 millimeters by 17.53 millimeters. The total volume of an average tooth scan was 2442.20 mm^3 according to the properties listed by VG Studio Max 2.0 software.

Of the twenty-five samples that were scanned, two had motion artifacts that made measurements inaccurate due to double images, and the other five were C-shaped canal systems. Eighteen samples were considered acceptable for the measurements that were planned in this study. In the original screening process, group 6 root classification teeth (C-shaped) were excluded in an attempt to take measurements in mandibular second molars other than those that are C-shaped. In this study, some teeth with root classifications in groups other than C-shaped actually had C-shaped canal systems.

Data were collected and reported on an Excel spreadsheet (raw data reported in Appendix A). The average value, standard deviation, and standard error of the mean were calculated for each pool of data concerning each anatomic measurement and are recorded on the spreadsheet. For some measurements, such as the distance from the mesial to the distal canal orifices, the total number of measurements was eighteen or one per sample. For other measurements, such as distance from major foramen to anatomic apex, there were multiple measurements per tooth resulting in 52 total measurements. The number of samples (N) for each measurement is reported on the raw data spreadsheet (see Appendix A).

RESULTS

Canal Configurations and Foramina

Using three-dimensional images obtained with the micro CT and software, canal configurations were assigned for each root. The number of apical foramen and accessory canals were also noted at this point as exit points either corresponding to the main canals of the root or those of a secondary nature. The following is a summary of Vertucci (V), Gulavibala (G), and Sert (S) configurations found in our samples and the representation of each configuration in the mesial and distal roots.

Canal Type	Mesial Root		Distal Root	
V1 = 1-1	2	(11.111%)	11	(61.111%)
V2 = 2-1	0		1	(5.556%)
V3 = 1-2-1	1	(5.556%)	5	(27.778%)
V4 = 2-2	1	(5.556%)	0	
V5 = 1-2	1	(5.556%)	0	
V6 = 2-1-2	3	(16.667%)	0	
V7 = 1-2-1-2	6	(33.333%)	1	(5.556%)
G9 = 3-1	1	(5.556%)	0	
G10 = 3-2	1	(5.556%)	0	
G12 = 2-1-2-1	1	(5.556%)	0	
S17 = 1-2-3-2	1	(5.556%)	0	

The most frequent mesial canal configuration found was Vertucci Type 7 (1-2-1-2), with 33% of samples showing this configuration. Vertucci Type 6 (2-1-2) was the next most frequently found configuration with 17% of samples showing this relationship.

Two samples (11%) had only one canal in the mesial root and three samples had three canals at some point down the mesial root (17%). There was a wide variety of configurations seen in the mesial root, with ten different catagories represented in eighteen teeth, and this is likely due to frequent communications between the canals such as isthmus connections.

The distal root samples showed fewer canal configuration types, with four represented in this group. Vertucci Type 1 (1) was the most commonly found system in eleven (61%) of the samples. The next most common configuration was Vertucci Type 53(1-2-1), seen in five samples (28%). Eleven (61%) of the distal canals had only one canal, with the remaining samples showing two canals at some point along their length.

Table 1 shows the mesial and distal canal configurations for each sample, the number of canals present in each tooth root, and the total number of canals found in each tooth. 11% (2/18) of the samples had two canals, 44% (8/18) of the samples had three canals, 33% (6/18) of the samples had four canals, and 11% (2/18) of the samples had five canals.

TABLE 1: Mesial and Distal Canal Configurations, Number of Canals per Root, and Number of Canals per Sample

Sample #	Canal Configuration		Number of Canals		Total Number of Canals
	Mesial	Distal	Mesial	Distal	
1	V1	V1	1	1	2
2	V6	V2	2	2	4
3	V6	V1	2	1	3

4	V7	V3	2	2	4
5	V5	V7	2	1	3
6	V7	V3	2	2	4
7	V7	V3	2	2	4
8	V7	V1	2	1	3
9	G9	V3	3	2	5
10	V7	V7	2	2	4
11	G10	V1	2	1	3
12	V6	V1	2	1	3
13	V3	V1	2	1	3
14	V7	V1	2	1	3
15	V4	V1	2	1	3
16	S17	V1	3	1	4
17	G12	V3	3	2	5
18	V1	V1	1	1	2

Pulp Floor Anatomy

The pulp floor anatomy in these samples was observed at a level 0.5 millimeters below the most coronal point of the pulp floor in an effort to describe the anatomy as the clinician would view it through a microscope upon clinical access. The mesial orifice area of the pulp floor was made up of one continuous structure connecting mesiobuccal and mesiolingual canals in sixteen of the samples, with only two samples including separate mesiobuccal and distobuccal orifices. Average size for the connected orifices in a buccolingual direction was 1.94 millimeters, with a standard deviation of 0.73. Mesiodistally, this orifice had an average of 0.56 millimeter width at the widest point, with a standard deviation of 0.16. Whether or not the orifices were connected or separate, overall the samples had an average distance from the most buccal and most lingual aspects of 2.11 millimeters for the mesial, with a standard deviation of 0.62. The distal orifice had a connected coronal aspect in seventeen cases, with separate orifices seen in only one sample. Average distance for the connected orifices from most buccal to most lingual was 1.31 millimeters with standard deviation of 0.55; for all distal samples, the average buccolingual distance was 1.47 millimeters with standard deviation of 1.02. Average mesiodistal dimension of the distal orifices was 1.01 millimeters with standard deviation of 0.31. Distance between the mesial orifices and the distal orifices as measured from the most mesial and distal points was on average 3.26 millimeters, with standard deviation of 0.58. The distance from the pulp floor to the furcation was on average 3.95 millimeters, with a standard deviation of 0.87 millimeters. The values had a wide range, with the smallest distance of 2.63 millimeters to the largest distance of 5.89 millimeters. Table 2 provides a summary of pulp floor anatomy dimensions.

TABLE 2: Pulp Floor Anatomy

	Mesial Total Buccolingual Distance (mm)	Distal Total Buccolingual Distance (mm)	Total Distance from Mesial to Distal Orifices (mm)	Distance from Pulp Floor to Furcation (mm)
AVERAGE	2.11	1.47	3.26	3.95
STANDARD DEVIATION	0.62	1.02	0.58	0.86
STANDARD ERROR OF THE MEAN	0.14	0.24	0.14	0.21

Root Wall Thickness

The thickness of the root wall from each of the main canals was recorded at one millimeter increments down the root. The average distance from the canal to the furcation at each level is reported in Table 3. At the one millimeter level, none of the samples exhibited a furcation so the first readings were at two millimeters. The average distances from the canals to the furcation were as follows: mesiobuccal canal 1.23 millimeters (SD = 0.19, SEM = 0.06), mesiolingual canal 1.29 millimeters (SD = 0.25, SEM = 0.08), distobuccal (or distal) canal 1.41 millimeters (SD = 0.25, SEM = 0.08), and distolingual canal 2.03 millimeters (SD = 0.15, SEM = 0.08). The root wall thickness measurements are shown for the first ten millimeters down the root. In the distal canal, there were no distolingual canals present at 8, 9 and 10 millimeters.

TABLE 3: Thickness of the Root Wall

Distance Along Root in Millimeters	MB Canal	ML Canal	DB (or D) Canal	DL Canal
1.0	No furcation	No furcation	No furcation	-
2.0	1.47	1.71	1.83	-
3.0	1.40	1.43	1.70	-
4.0	1.42	1.51	1.61	2.21
5.0	1.33	1.32	1.42	2.04
6.0	1.25	1.28	1.27	1.84
7.0	1.21	1.23	1.25	2.01
8.0	1.08	1.06	1.18	-

9.0	1.04	1.18	1.23	-
10.0	0.91	0.86	1.18	-

Canal Dimensions

The average dimensions of the canals at each level along the root are reported in Table 4. For the mesiobuccal canal, the average mesiodistal distance was 0.30 millimeters (SD = 0.04, SEM = 0.09) and the average buccolingual distance was 1.07 millimeters (SD = 0.21, SEM = 0.07). The mesiolingual canal averaged 0.27 millimeters (SD = 0.04, SEM = 0.01) wide in a mesiodistal direction and 0.54 millimeters (SD = 0.13, SEM = 0.04) buccolingually. Canals in the distobuccal (or distal if only one canal was present) canal averaged a mesiodistal width of 0.55 millimeters (SD = 0.10, SEM = 0.03) and a buccolingual distance of 0.94 millimeters (SD = 0.20, SEM = 0.06). In those samples that had a distolingual canal, the mesiodistal dimension was 0.24 millimeters (SD = 0.05, SEM = 0.02) and the buccolingual width was 0.26 millimeters (SD = 0.07, SEM = 0.04). Measuremenst for the first ten millimeters are reported in Table 4. There was no distolingual canal present in any of the samples in millimeters 8, 9, and 10.

TABLE 4: Average Dimensions of the Canals

Distance Down Root (mm)	Mesial				Distal			
	MB Canal		ML Canal		DB Canal		DL Canal	
	MD	BL	MD	BL	MD	BL	MD	BL

1.0	0.38	1.38	0.31	0.65	0.64	0.94	-	-
2.0	0.30	1.16	0.29	0.63	0.57	0.97	-	-
3.0	0.31	1.18	0.29	0.67	0.59	1.12	-	-
4.0	0.30	0.94	0.29	0.63	0.56	1.24	0.22	0.17
5.0	0.31	1.17	0.32	0.54	0.52	1.11	0.31	0.34
6.0	0.30	1.30	0.28	0.50	0.45	1.03	0.22	0.25
7.0	0.27	0.99	0.24	0.63	0.42	0.87	0.22	0.28
8.0	0.30	1.02	0.23	0.26	0.40	0.72	-	-
9.0	0.25	0.83	0.24	0.46	0.39	0.64	-	-
10.0	0.25	0.73	0.21	0.46	0.38	0.72	-	-

Calcifications

Calcifications were reported as being either present or absent in the pulp chamber and in the canals. In the pulp chamber three of the samples did not have calcifications, while fifteen samples did exhibit calcifications. Within the canal spaces, four teeth did not have calcifications and fourteen samples were calcified. Three samples (17%) were free from calcifications in both the pulp chamber and the canals, while fourteen teeth (78%) had calcifications present in both the pulp chamber and within the canals. Only one sample (6%) had calcified material in the pulp chamber while the canals remained calcification-free.

Apical Anatomy

In the eighteen teeth studied, there were fifty-two major foramen which were found to deviate an average of 0.89 millimeters from the anatomic apex (SD = 0.34, SEM = 0.05). The minor constriction was on average 0.25 millimeters in width at the most narrow point (SD = 0.07, SEM = 0.01). When measuring the distance from the major constriction to the minor constriction, the average was 0.54 millimeters (SD = 0.18, SEM = 0.03).

TABLE 5: Summary of Apical Anatomy

	Major Foramen to Anatomic Apex (mm)	Width of Minor Constriction (mm)	Minor Constriction to Major Foramen (mm)
Average	0.89	0.25	0.54
Standard Deviation	0.34	0.07	0.18
Standard Error of the Mean	0.05	0.01	0.03

The presence of lateral, secondary, and accessory canals in the apical region were recorded once the major foramen were identified and measured. In the apical region of the mesial root, eight (44.444%) of the roots had only major foramen, three (16.667%) of the roots had one lateral, secondary, or accessory canal, four (22.222%) of the roots had two lateral, secondary, or accessory canals, and three (16.667%) of the roots had three lateral, secondary, or accessory canals. The distal root had fewer lateral, secondary, or accessory canals overall, with eleven (61.111%) roots having none, and seven (38.889%) roots with one. The presence of lateral, secondary, and accessory canals in the other regions of the root and the furcation were not recorded in this study.

DISCUSSION

A wide variety of root canal configurations were seen in the mesial root, with ten different catagories represented in eighteen teeth. The distal canal expressed less variety in form, with four canal configuration types seen in the samples investigated. The multiple forms seen in this study are likely due to frequent communications between the canals such as isthmuses that may be difficult to appreciate with other methods of investigation. In this study, there were only eighteen total samples. If the number of samples were increased, the number of catagories represented may be even more diverse. Many of the more complex canals present in the middle portion of the root or irregular isthmuses would not be detectable clinically or on periapical radiographs.

Number of canals seen in the mandibular second molars investigated in this study had a higher percentage of two canal and five canal teeth represented compared to classic studies of mandibular second molars. In contrast to the retrospective *in vivo* study by Hartwell & Bellizzi which found two canals 4.1% of the time, three canals 89.4% of the time, four canals 5.5% of the time, this study had 11% of samples with two canals, 44% with three canals, 33% with four canals, and 11% with five canals. It is plausible that the higher representation of four and five canal samples is due to the high resolution available using the micro CT scans, which allows identification of small or shorter additional canals. However, the finding of a higher percentage of two canal mandibular second molars would not be expected in a micro CT study. It is possible that due to smaller number of samples, this study had a higher percentage of mandibular second molars with two canals by chance. The strong representation of mandibular molars with two canals does suggest that these teeth exhibit a variety of forms, ranging from rather simple to quite complex. Unfortunately, it is difficult to tell one from another clinically.

The pulp floor has been described in terms of the symmetry of orifices along the mesiodistal midline of the tooth. In this study, the averaged distances between the orifices were reported. The limitation of this data is that there was a good deal of variability in the distances between the orifices. The distance from the pulp floor to the furcation has been reported as 2.96 ± 0.78 millimeters (Deutsch & Musikant, 2004). In this study, this distance was on average 3.95 millimeters with a standard deviation of 0.86. Both studies included heavily restored teeth, but in this study, no access preparation was made. Perhaps there are calcifications present on the pulp floor in this study that account for a greater distance on average from pulp floor to furcation, or differences are due to low sample size.

The area in the first mandibular molar that is thought to be the most vulnerable to strip perforation is located 1.5 millimeters below the furcation, and has been reported to be 1.2-1.3 millimeters thick (Berutti & Fedon, 1992). In this study, the average root wall thickness over ten millimeters of root length was 1.23 millimeters for the mesiobuccal canal, 1.29 millimeters in the mesiolingual canal, and 1.41 millimeters in the distal canal. There was a general trend of thicker root structure more coronally, and thinner structure toward the apical. For example, the mesiobuccal canal started with an average root thickness of 1.47 millimeters at two millimeters, decreasing in thickness to 0.91 millimeters at ten millimeters down the root. The mesiobuccal canal had the thinnest root wall compared to the mesiolingual and distal canals, and the very dramatic clinical point is that the root wall is generally thin enough that iatrogenic errors that deviate the canal or procedures that enlarge the canal have the potential to perforate the root at any level.

The majority of the teeth (78%) in this study had calcifications present in the pulp chamber and within the canals. The samples were teeth with large fillings and evidence of wear, which may have contributed to the high degree of calcification seen in the teeth studied. Another possible factor may be the ages of the patients from which the teeth were extracted, which are not known but are likely to be fifty and older based on the population served at the Veteran's Administration Medical Center Dental Clinic. Periodontal issues may also have had an impact of the calcification rate, but the degree to which the teeth were affected by periodontal disease is not known in this study. The calcifications were extensive enough that they could block progress down canals. Interestingly, the canals themselves were on average large enough for files to easily advance. In the mesiobuccal canal, the mesiodistal average dimension was 0.30 millimeters, with 1.07 millimeters in the buccolingual direction. This measurement does not take into account canal curvature or calcifications, which could change the clinical difficulty of instrumentation to a great degree. In the teeth that exhibited calcification, there was a great deal of calcified material present which could easily block progress of an instrument down a canal. In this study, there was not an attempt to rate the degree of calcification in the pulp chamber or canals. This may be an area to address in future studies.

Apical anatomy findings were consistent with those reported in previous studies. The distance from the major foramen to the anatomic apex on average was 0.89 millimeters in this study, as compared to 0.59 (Burch & Hulen, 1972) and 0.61 (Kuttler, 1955). An average minor constriction width was found to be 0.25 millimeters in this study, which compares rather closely to 0.189 millimeters (Stein & Corcoran, 1990) found in previous studies. The proximity of the major foramen to the minor constriction averaged 0.54 millimeters in this study, with 0.72 millimeters (Stein & Corcoran, 1990) for this distance found previously. Lateral, secondary, and accessory canals were present in 55.556% of mesial roots in the apical region and 38.889% of distal roots in the apical region. Previous studies reported 17% of roots with lateral, secondary, and accessory canals present in the apical third (DeDeus, 1975). The higher frequency of these structures found in this study is likely related to the detail available in images from the micro CT.

CONCLUSIONS

This study of mandibular second molars investigated many aspects of tooth anatomy using micro CT generated images. Some aspects of the anatomy were simply a confirmation of the findings of previous studies, while other measurements provided data for the second mandibular molar that had not been previously reported. When examining the anatomy of teeth using micro CT, the complexity of the canal systems makes it clear that methods of cleaning and shaping must depend heavily on those that can reach places that files cannot.

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Appendix A:

Key for Raw Data Spreadsheets:

MB = mesiobuccal
ML = mesiolingual
DB = distobuccal
DL = distolingual
MF = major foramen
AA = anatomic apex
MC = minor constriction
M/M = major constriction to minor constriction
Fl to furc = pulp floor to furcation
Calc Ch = calcifications of chamber
Calc C = calcifications of canal
Thin = thickness of root wall
AV = average
SD = standard deviation
SEM = standard error of the mean

Sample #	#18/#31	MF to AA				Foramina	
		MB	ML	DB (orD)	DL	# M root	MC MB
1	31	0.91		0.73		1	0.33
2	31	0.43	0.77	1.35		2(1)	0.2
3	31	0.68	0.78	0.95		2(3)	0.31
4	31	0.77	0.55	0.74	1	2	0.3
5	18	0.3	0.55	0.74		2	0.21
6	18	0.62	1.1	1.27		2	0.22
7	31	0.63	0.72	0.59		2	0.18
8	31	0.93	0.81	1.95		2(2)	0.21
9	31	0.34		1.22		1	0.3
10	18	1.45	1.2	0.8		2(2)	0.19
11	31	1.25	1.34	0.96		2(2)	0.15
12	18	0.65	1.38	0.85		2(3)	0.24
13	18	0.66		1.12		1(2)	0.2
14	31	0.67	1.3	1.39		2	0.19
15	31	0.82	0.6	0.56		2(1)	0.17
16	31	0.63	0.53	0.64		2(1)	0.23
17	31	1.13	1	0.62	0.67	2(3)	0.21
18	18	1.14		1.59		1	0.29
AVERAGE		0.778333	0.902143	1.003889	0.835		0.229444
Standard Deviation		0.309976	0.312267	0.388892	0.233345		0.05352
SEM		0.073062	0.083457	0.091663	0.165		0.012615
N for measurement		18	14	18	2	18	18

MF to AA all AVER	0.891923	MC all AVER	0.253036
MF to AA St DEV	0.34278	MC all St DEV	0.073606
MF to AA SEM	0.047535	MC all SEM	0.009836
N	52	N	56

MC ML	M/M MB	M/M ML	# D root	MC DB	MC DL	M/M DB	M/M DL
	0.6		1	0.27		0.28	
0.32	0.38	0.63	1	0.36		0.66	
0.2	0.66	0.57	1(1)	0.32		0.64	
0.28	0.41	0.44	2	0.24	0.28	0.43	0.39
0.16	0.33	0.37	1(1)	0.33	0.34	0.44	0.35
0.18	0.4	0.45	1(1)	0.25	0.26	0.57	0.39
0.36	0.44	0.7	1(1)	0.25	0.16	0.69	0.72
0.22	0.49	0.53	1	0.44		0.94	
	0.48		1	0.31		0.86	
0.17	0.63	0.48	1(1)	0.32	0.19	0.57	0.73
0.21	0.44	0.45	1	0.46		0.96	
0.25	0.51	0.58	1	0.22		0.46	
	0.36		1	0.43		0.9	
0.26	0.39	0.28	1	0.28		0.55	
0.12	0.27	0.29	1(1)	0.27		0.63	
0.15	0.3	0.35	1	0.22		0.46	
0.21	0.55	0.62	2(1)	0.27	0.21	0.42	0.79
	0.72		1	0.27		1.06	
0.220714	0.464444	0.481429		0.306111	0.24	0.64	0.561667
0.067307	0.127058	0.129962		0.073656	0.06603	0.221306	0.204589
0.017989	0.029948	0.034734		0.017361	0.026957	0.052162	0.083523
14	18	14	18	18	6	18	6

M/M AV	0.535536
M/M SD	0.184311
M/M SEM	0.02463
N	56

Canal type		Root Lgth		Pulp Floor			
M/D	fl to furc	M	D	MB MD	MB BL	ML MD	ML BL
V1/V1	4.62	12	12.29	0.5	1.8		
V6/V2	3.63	11.96	12.7	0.69	3.1		
V6/V1	3.17	11.49	10.84	0.91	1.57		
V7/V3	4.51	11.75	12.71	0.46	3.38		
V5/V1	4.46	11.7	12.53	0.4	1.8		
V7/V3	4.57	11.9	12.34	0.24	1.95		
V7/V3	2.99	14.05	14.7	0.77	2.89		
V7/V1	4.81	14.17	14.21	0.59	2.35		
G1/V3	3.23	11.17	11.35	0.5	1.85		
V7/V7	4.62	12.1	12.43	0.66	2.56		
G2/V1	4.49	11.2	11.39	0.56	1.24	0.34	1.19
V6/V1	3.9	11.55	11.46	0.36	2.41		
V3/V1	3.27	12.48	13.77	0.61	1.97		
V7/V1	5.89	11.18	11.54	0.46	1.73		
V4/V1	4.33	10.01	10.53	0.48	0.48	0.34	0.2
S17/V1	2.77	9.32	8.82	0.63	1.2		
G4/V3	3.26	11.56	13.25	0.6	1.36		
V1/V1	2.63	11.09	11.09	0.62	1.3		
	3.952778	11.70444	12.10833	0.557778	1.941111	0.34	0.695
	0.8752	1.147161	1.415516	0.155016	0.737228	0	0.700036
	0.206287	0.270389	0.33364	0.036538	0.173766		0.495
18	18	18	18	18	18	2	2

Root Length AV		11.90639
Root Length SD		1.286217
Root Length SEM		0.21437
N		36

M BL total	D BL total	DB MD	DB BL	DL MD	DL BL	M to D	Calc Ch
1.8	1.95	0.81	1.95			1.8	n
3.1	0.98	0.79	0.98			4.2	y
1.57	0.76	0.99	0.76			3.41	n
3.38	1.92	1.08	1.92			3.53	y
1.8	0.84	1.11	0.84			3.71	y
1.95	1.49	0.33	1.49			2.92	y
2.89	5.02	1.02	2.13	0.77	2.89	3.23	y
2.35	1.36	1.36	1.36			2.98	y
1.85	1.32	0.69	1.32			3.18	y
2.56	2.32	1.54	2.32			3.39	y
2.43	1.51	1.26	1.51			3.65	y
2.41	0.74	1.07	0.74			3.19	y
1.97	1.52	1.32	1.52			4.33	y
1.73	0.83	0.65	0.83			2.56	y
2.48	0.62	1.03	0.62			2.88	y
1.2	0.65	0.75	0.65			3.17	n
1.36	1.77	1	1.77			3.03	y
1.3	0.91	1.4	0.91			3.6	y
							3n:15y
2.118333	1.472778	1.011111	1.312222	0.77	2.89	3.264444	
0.62201	1.019774	0.305246	0.545792			0.576186	
0.146609	0.240363	0.071947	0.128644			0.135808	
18	18	18	18	1	1	18	18

	1.0mm						
Calc C	MB thin	MB MD	MB BL	ML thin	ML MD	ML BL	DB thin
n	N/A	0.69	0.66	N/A			N/A
y	N/A	0.32	0.83	N/A	0.32	0.96	N/A
n	N/A	0.54	2.3				N/A
n	N/A	0.34	0.6	N/A	0.43	0.76	N/A
y	N/A	0.36	1.81				N/A
y	N/A	0.19	0.72	N/A	0.24	0.54	N/A
y	N/A	0.44	1.93				N/A
y	N/A	0.31	1.64	N/A	0.13	0.22	N/A
y	N/A	0.48	1.85				N/A
y	N/A	0.27	0.49	N/A	0.34	0.83	N/A
y	N/A	0.4	1.5	N/A	0.32	0.41	N/A
y	N/A	0.34	1.4	N/A	0.36	0.86	N/A
y	N/A	0.39	1.65	N/A			N/A
y	N/A	0.34	1.7				N/A
y	N/A	0.28	0.25	N/A	0.31	0.62	N/A
n	N/A	0.33	1.71				N/A
y	N/A	0.32	1.7				N/A
y	N/A	0.52	2.1				N/A
4n:14y							
		0.381111	1.38		0.30625	0.65	
		0.117167	0.617204		0.088791	0.25077	
		0.027617	0.145476		0.031393	0.088661	
18		18	18		8	8	

					2.0mm		
DB MD	DB BL	DL thin	DL MD	DL BL	MB thin	MB MD	MB BL
0.53	1.12	N/A			0.99	0.65	0.98
0.16	0.57					0.22	0.35
0.82	0.67				2.16	0.31	0.84
0.58	1.18					0.27	0.35
0.59	0.79					0.26	0.33
0.58	0.83					0.15	0.75
0.5	1.32					0.26	2.79
0.59	0.74					0.31	2.31
0.51	0.9				1.48	0.29	0.64
1	1.69					0.34	1.39
0.92	1.31					0.42	0.64
0.58	0.62					0.28	1.62
0.98	1.15				1.59	0.4	0.63
0.43	0.81					0.28	2.16
0.65	0.42				1.13	0.25	0.2
0.53	0.6				1.58	0.25	1.48
0.7	1.49					0.11	0.97
0.94	0.78				1.32	0.28	2.46
0.643889	0.943889				1.464286	0.296111	1.160556
0.216988	0.351219				0.381001	0.114745	0.808764
0.051145	0.082783				0.144005	0.027046	0.190628
18	18				7	18	18

ML thin	ML MD	ML BL	DB thin	DB MD	DB BL	DL thin	DL MD
			1.46	0.55	0.68		
N/A	0.16	0.38	N/A	0.28	0.51		
1.36	0.41	0.94	1.87	0.7	0.72		
N/A	0.37	1	N/A	0.53	1.05		
			N/A	0.59	1		
N/A	0.26	0.63	N/A	0.52	0.73		
			N/A	0.44	1.61		
N/A	0.16	0.19	N/A	0.62	1.49		
1.33	0.18	0.65	1.74	0.45	0.71		
N/A	0.34	1.15	N/A	0.73	1.39		
N/A	0.41	0.53	N/A	0.78	1.14		
N/A	0.26	0.75	N/A	0.56	0.77		
1.8	0.32	0.54	2.25	0.73	1.07		
			N/A	0.49	0.94		
2.34	0.31	0.13	2.2	0.59	0.6		
			1.59	0.4	0.84		
N/A	0.24	0.61	N/A	0.6	1.49		
			1.72	0.78	0.78		
1.7075	0.285	0.625	1.832857	0.574444	0.973333		
0.473242	0.089899	0.307852	0.297081	0.136219	0.333167		
0.236621	0.025952	0.092821	0.070023	0.032107	0.078528		
4	12	11	18	18	18		

	3.0mm						
DL BL	MB thin	MB MD	MB DL	ML thin	ML MD	ML BL	DB thin
	1.14	0.36	3.59				1.7
	1.21	0.19	0.17	0.96	0.22	0.16	1.17
	1.14	0.31	0.87	0.76	0.34	1.13	1.23
	1.94	0.33	0.31	1.99	0.37	0.63	2.33
	1.82	0.33	0.69	1.53	0.33	0.88	2.05
	N/A	0.15	0.83	N/A	0.14	0.28	N/A
	1.32	0.37	0.91	1.22	0.28	0.8	1.36
	N/A	0.25	0.94	N/A	0.16	1.05	N/A
	1.11	0.24	0.72	0.93	0.18	0.59	1.53
	1.11	0.37	1.73	1.3	0.44	0.66	1.77
	1.62	0.41	0.53	1.65	0.44	0.46	2
	1.35	0.26	1.62	1.48	0.24	0.49	1.66
	1.23	0.58	0.37	1.45	0.3	0.56	1.8
	N/A	0.4	2.34				N/A
	1.85	0.25	0.26	2.44	0.28	1.06	2.26
	1.21	0.28	1.38				1.18
	1.41	0.24	2.31				1.87
	1.53	0.26	1.74				1.53
	1.399333	0.31	1.183889	1.428182	0.286154	0.673077	1.696
	0.286518	0.098339	0.900419	0.487418	0.097685	0.299705	0.369726
	0.073979	0.023179	0.212231	0.146962	0.027093	0.083123	0.095463
	15	18	18	11	13	13	15

					4.0mm		
DB MD	DB BL	DL thin	DL MD	DL BL	MB thin	MB MD	MB DL
0.73	0.84				1.18	0.39	1.81
0.73	1.29				1.58	0.22	0.25
0.63	0.72				0.77	0.34	0.73
0.44	1.42				1.81	0.4	0.51
0.53	1.09				1.77	0.36	0.53
0.49	0.89				2.34	0.12	1
0.29	1.97				1.39	0.29	1.65
0.59	1.61				1.3	0.27	0.79
0.21	0.55				0.9	0.24	0.6
0.76	1.66				1	0.37	0.68
0.83	1.31				1.59	0.41	0.56
0.62	1.03				1.19	0.22	2.26
0.71	1.01				1.21	0.36	0.42
0.62	0.89				1.92	0.34	0.52
0.51	0.87				1.93	0.2	0.22
0.43	0.71				1.08	0.33	1.1
0.68	1.36				1.1	0.2	2.13
0.76	0.96				1.5	0.34	1.14
0.586667	1.121111				1.42	0.3	0.938889
0.168523	0.376765				0.416512	0.083243	0.626718
0.039721	0.088804				0.098173	0.019621	0.147719
18	18				18	18	18

ML thin	ML MD	ML BL	DB thin	DB MD	DB BL	DL thin	DL MD
			1.6	0.63	0.93		
1.29	0.16	0.32	1.68	0.79	2.24		
0.81	0.32	1.35	1.21	0.73	0.61		
1.93	0.27	0.36	2.39	0.4	1.54		
1.39	0.3	0.32	1.87	0.48	1.22		
1.65	0.21	0.19	1.77	0.42	0.94		
1.21	0.29	1.56	1.28	0.41	2.04		
1.73	0.19	0.71	1.76	0.5	1.67		
0.81	0.19	0.69	1.28	0.37	0.55		
1.36	0.42	0.66	1.67	0.68	1.88		
1.9	0.42	0.49	2	0.68	1.31		
			1.29	0.58	0.88		
1.21	0.33	0.48	1.56	0.59	1.26		
1.37	0.28	0.69	1.52	0.64	0.9		
2.91	0.37	0.42	2.13	0.56	1.13	2.21	0.22
			0.98	0.3	0.85		
			1.51	0.63	1.49		
			1.45	0.62	0.83		
1.505385	0.288462	0.633846	1.608333	0.556111	1.237222	2.21	0.22
0.549327	0.084936	0.402338	0.349659	0.135653	0.486836		
0.152356	0.023557	0.111588	0.082416	0.031974	0.114748		
13	13	13	18	18	18	1	1

	5.0mm						
DL BL	MB thin	MB MD	MB DL	ML thin	ML MD	ML BL	DB thin
	1.24	0.57	1.94				1.56
	1.36	0.29	0.22	1.36	0.29	0.35	1.23
	0.73	0.34	1.78	0.66	0.39	1.52	1.17
	1.72	0.33	0.76	1.79	0.3	0.72	1.98
	1.54	0.3	0.4	1.23	0.33	0.26	1.75
	2.08	0.14	0.8	1.52	0.21	0.15	1.59
	1.41	0.29	2.45	1.26	0.29	0.94	1.1
	1.22	0.22	3.08				1.17
	0.96	0.21	1.43	0.8	0.18	0.24	1.06
	1.54	0.39	0.54	1.44	0.51	0.47	1.68
	1.38	0.44	0.47	1.7	0.32	0.39	1.61
	1.02	0.26	2.18				1.1
	1.05	0.36	0.62	0.94	0.34	0.47	1.43
	1.42	0.37	0.55	1.18	0.34	0.56	1.29
0.17	1.72	0.14	0.17	2	0.34	0.36	2.12
	1.1	0.4	1.05				0.9
	1.11	0.16	1.95				1.44
	N/A	0.34	0.6				N/A
0.17	1.329412	0.308333	1.166111	1.323333	0.32	0.535833	1.422353
	0.332199	0.110892	0.862992	0.400598	0.08323	0.378309	0.339844
	0.0783	0.026138	0.203409	0.115643	0.024027	0.109208	0.082424
1	18	18	18	12	12	12	17

					6.0mm		
DB MD	DB BL	DL thin	DL MD	DL BL	MB thin	MB MD	MB DL
0.66	1.02				1.16	0.52	1.81
1.17	2.15				1.37	0.22	0.38
0.57	0.64				0.64	0.39	3.29
0.37	1.43				1.82	0.34	1.99
0.43	0.93				1.29	0.23	0.24
0.35	1.06				1.66	0.22	0.53
0.37	2.08				1.28	0.18	3.83
0.49	1.42				1.27	0.22	2.53
0.37	0.55				0.9	0.26	0.34
0.73	1.64				1.76	0.32	0.37
0.59	1.05				1.43	0.39	0.44
0.41	0.69				0.84	0.17	1.73
0.7	1.26				1.29	0.37	1.88
0.52	0.84				1.1	0.37	0.58
0.2	0.11	2.04	0.31	0.34	1.47	0.22	0.22
0.25	0.6				0.88	0.45	1.4
0.57	1.73				1.12	0.2	1.51
0.57	0.73				N/A	0.34	0.41
0.517778	1.107222	2.04	0.31	0.34	1.251765	0.300556	1.304444
0.220122	0.550057				0.325945	0.101139	1.10483
0.051883	0.12965				0.079053	0.023839	0.260411
18	18	1	1	1	17	18	18

ML thin	ML MD	ML BL	DB thin	DB MD	DB BL	DL thin	DL MD
			1.4	0.78	1.22		
1.06	0.22	0.86	1.11	0.63	1.83		
			1.08	0.41	0.53		
			1.86	0.37	1.07		
1.19	0.26	0.29	1.19	0.41	0.97		
1.56	0.24	0.19	1.46	0.31	0.92		
			1.06	0.29	2.15		
			0.95	0.53	1.11		
0.77	0.24	0.98	1	0.37	0.71		
1.61	0.32	0.46	1.52	0.7	1.51		
1.45	0.32	0.32	1.41	0.58	0.97		
			1.2	0.32	0.6		
			1.49	0.68	1.15		
1.13	0.37	0.55	1.15	0.4	0.74		
1.48	0.28	0.31	1.76	0.14	0.15	1.84	0.22
			0.76	0.3	0.8		
			1.14	0.44	1.57		
			N/A	0.42	0.49		
1.28125	0.28125	0.495	1.267059	0.448889	1.027222	1.84	0.22
0.291618	0.051391	0.286007	0.291049	0.168065	0.499079		
0.103103	0.01817	0.101119	0.07059	0.039613	0.117634		
8	8	8	17	18	18	1	1

	7.0mm						
DL BL	MB thin	MB MD	MB BL	ML thin	ML MD	ML BL	DB thin
	0.88	0.55	1.28				1.22
	1.16	0.19	0.54	0.79	0.19	1.42	1.09
	0.7	0.37	1.16	0.72	0.3	0.91	0.86
	1.59	0.37	1.28				1.53
	1.18	0.17	0.31	1.19	0.2	0.29	1.16
	1.82	0.18	0.12	1.54	0.14	0.12	1.36
	0.92	0.18	3.43				1.17
	1.33	0.31	2.02				1.25
	0.86	0.21	0.48	0.78	0.16	0.79	1.01
	1.4	0.41	0.37	1.47	0.44	0.42	1.47
	1.3	0.41	0.39	1.09	0.24	0.29	1.31
	0.94	0.17	1.14				1.12
	1.31	0.29	1.39				1.68
	1.14	0.25	1.63				1.12
0.25	1.59	0.11	0.15	2.24	0.28	0.32	1.89
	1.13	0.25	0.25	1.21	0.23	1.15	0.56
	1.24	0.13	1.39				1.36
	N/A	0.36	0.47				N/A
0.25	1.205294	0.272778	0.988889	1.225556	0.242222	0.634444	1.244706
	0.295087	0.118759	0.837137	0.481069	0.090661	0.451362	0.307126
	0.071569	0.027992	0.197315	0.160356	0.03022	0.150454	0.074489
1	17	18	18	9	9	9	17

					8.0mm		
DB MD	DB BL	DL thin	DL MD	DL BL	MB thin	MB MD	MB BL
0.73	1.02				0.88	0.57	1.07
0.67	1.42				0.9	0.44	0.95
0.41	0.56				0.82	0.33	0.8
0.4	1.51				1.46	0.23	1.16
0.4	0.74				0.89	0.19	0.24
0.24	0.59				1.75	0.14	0.62
0.4	1.75				0.81	0.22	3.21
0.4	0.99				1.38	0.28	1.42
0.42	0.61				0.78	0.21	1.66
0.61	1.02				0.84	0.66	1.07
0.41	0.66				0.76	0.22	0.22
0.24	0.39				0.94	0.17	1.14
0.56	1				1.33	0.39	1.03
0.34	0.57				1.26	0.22	1.14
0.17	0.26	2.01	0.22	0.28	1.27	0.17	0.18
0.41	0.55				1.08	0.33	0.5
0.37	1.63				1.13	0.19	1.68
0.44	0.39				N/A	0.41	0.31
0.423333	0.87	2.01	0.22	0.28	1.075294	0.298333	1.022222
0.144018	0.451716				0.288858	0.145572	0.719334
0.033945	0.10647				0.068084	0.034312	0.169549
18	18	1	1	1	18	18	18

ML thin	ML MD	ML BL	DB thin	DB MD	DB BL	DL thin	DL MD
			1.16	0.73	0.94		
0.83	0.16	0.1	1.08	0.5	1.23		
1.03	0.2	0.41	0.86	0.37	0.39		
			1.29	0.33	0.4		
1.03	0.18	0.2	1.2	0.3	0.39		
1.43	0.21	0.18	1.52	0.25	0.33		
			1.06	0.4	1.46		
			1.42	0.44	0.94		
			0.87	0.58	0.66		
1.08	0.37	0.32	1.23	0.52	0.81		
0.89	0.19	0.22	1.12	0.44	0.73		
			1.12	0.24	0.39		
			1.42	0.44	1.02		
			1.1	0.31	0.46		
1.34	0.25	0.31	1.65	0.42	0.48		
0.87	0.25	0.35	0.48	0.35	0.45		
			1.48	0.24	1.51		
			N/A	0.36	0.34		
1.0625	0.22625	0.26125	1.18	0.401111	0.718333		
0.218877	0.066103	0.102739	0.28324	0.126625	0.387606		
0.077385	0.023371	0.036324	0.068696	0.029846	0.09136		
8	8	8	17	18	18		

	9.0mm						
DL BL	MB thin	MB MD	MB BL	ML thin	ML MD	ML BL	DB thin
	0.88	0.5	0.97				1.02
	0.86	0.32	0.5	0.79	0.16	0.13	1.17
	0.95	0.32	0.5	1.36	0.2	0.64	0.88
	1.06	0.23	0.86				1.26
	1.15	0.17	0.21	0.91	0.18	0.22	1.19
	1.76	0.17	0.1	1.27	0.21	0.3	1.71
	0.91	0.18	2.74				0.95
	1.3	0.22	1.1				1.28
	0.69	0.18	1				0.85
	0.7	0.26	0.59	1.01	0.34	1.2	1.15
	1.57	0.39	0.49	2.07	0.34	0.46	2.02
	0.92	0.22	0.6				1.07
	1.19	0.26	0.87				1.21
	1.3	0.22	0.92				1.04
	0.43	0.1	0.14	0.84	0.22	0.24	1.43
	1.04	0.18	2.3				1.37
	N/A	0.28	0.26				N/A
	1.044375	0.247059	0.832353	1.178571	0.235714	0.455714	1.225
	0.334345	0.095509	0.711649	0.447602	0.073905	0.369768	0.303337
	0.083586	0.023164	0.1726	0.169178	0.027933	0.139759	0.075834
	16	17	17	7	7	7	16

					10.0mm		
DB MD	DB BL	DL thin	DL MD	DL BL	MB thin	MB MD	MB BL
0.48	0.88				1.02	0.52	0.55
0.42	0.41				0.82	0.32	0.28
0.28	0.24				1.02	0.24	0.34
0.23	0.53				0.8	0.3	0.73
0.31	0.29				0.81	0.14	0.19
0.28	0.28				0.77	0.2	0.61
0.37	1.28				1.03	0.33	2.56
0.34	0.59				1.45	0.25	0.81
0.29	0.4				0.61	0.24	0.32
0.45	0.93				0.86	0.24	1.64
0.68	1.24						
0.22	0.28				0.97	0.11	0.22
1.01	1.27				1.25	0.3	0.78
0.28	0.43				0.99	0.22	1
0.25	0.27						
0.34	1.23				0.37	0.11	0.12
0.34	0.39						
0.386471	0.643529				0.912143	0.251429	0.725
0.196149	0.400499				0.261598	0.10531	0.665163
0.047573	0.097135				0.069915	0.028145	0.177772
17	17				14	14	14

ML thin	ML MD	ML BL	DB thin	DB MD	DB BL	DL thin	DL MD
			1.34	0.46	0.56		
0.83	0.22	0.35	1.14	0.48	0.5		
0.95	0.26	1.47					
			1.06	0.27	0.53		
0.9	0.18	0.21	1.19	0.27	0.31		
			0.95	0.47	1.02		
			1.47	0.29	0.44		
0.32	0.21	0.37					
			1.1	0.37	1.2		
0.98	0.19	0.15	1.05	0.17	0.22		
			1.33	0.77	0.98		
			0.99	0.31	0.44		
1.15	0.21	0.23	1.3	0.26	1.72		
0.855	0.211667	0.463333	1.174545	0.374545	0.72		
0.258376	0.027869	0.500347	0.165733	0.164946	0.455302		
0.105482	0.011377	0.204266	0.04997	0.049733	0.137279		
6	6	6	11	11	11		

	11.0mm						
DL BL	MB thin	MB MD	MB BL	ML thin	ML MD	ML BL	DB thin
	1.06	0.26	0.34				1.14
	0.67	0.16	0.35	0.69	0.29	0.51	1.11
	0.8	0.3	0.56	0.44	0.24	0.3	0.97
	0.52	0.12	0.11	0.54	0.13	0.15	1.18
	1.05	0.26	2.23				1.1
	N/A	0.25	0.49				N/A
	0.15	0.32	0.37				0.17
	0.85	0.33	0.56				1.47
	1.22	0.11	0.14				1.44
	0.79	0.234444	0.572222	0.556667	0.22	0.32	1.0725
	0.343511	0.083981	0.642257	0.125831	0.081854	0.180831	0.402909
	0.114504	0.027994	0.214086	0.072648	0.047258	0.104403	0.14245
	9	9	9	3	3	3	8

					12.0mm		
DB MD	DB BL	DL thin	DL MD	DL BL	MB thin	MB MD	MB BL
0.37	0.41				0.67	0.21	0.29
0.47	0.5						
0.37	0.46						
0.21	0.22						
0.4	0.8				0.88	0.26	1.46
0.22	0.46				N/A	0.19	0.4
0.32	0.88						
0.94	0.77						
0.26	0.47	0.7	0.12	0.13			
0.395556	0.552222	0.7	0.12	0.13	0.775	0.22	0.716667
0.221535	0.216031				0.148492	0.036056	0.646091
0.073845	0.07201				0.085732	0.020817	0.373021
9	9	1	1	1	2	3	3

ML thin	ML MD	ML BL	DB thin	DB MD	DB BL	DL thin	DL MD
			0.95	0.26	0.3		
			0.88	0.3	0.43		
			1.17	0.48	0.77		
			N/A	0.13	0.3		
			1	0.2925	0.45		
			0.151327	0.144539	0.221961		
			0.087369	0.07227	0.11098		
			3	4	4		

	13						
DL MD	MB thin	MB MD	MB BL	ML thin	ML MD	ML BL	DB thin
	0.26	0.12	0.12	0.68	0.12	0.18	1.22
	0.26	0.12	0.12	0.68	0.12	0.18	1.22
	1	1	1	1	1	1	1

DB MD	DB BL
0.21	0.19
0.21	0.19
1	1

Distance	Mesial canal dimensions				Distal canal dimensions		
	MB canal		ML canal		DB/D canal		DL
	MD	BL	MD	BL	MD	BL	MD
1	0.38	1.38	0.31	0.65	0.64	0.94	
2	0.3	1.16	0.29	0.63	0.57	0.97	
3	0.31	1.18	0.29	0.67	0.59	1.12	
4	0.3	0.94	0.29	0.63	0.56	1.24	0.22
5	0.31	1.17	0.32	0.54	0.52	1.11	0.31
6	0.3	1.3	0.28	0.5	0.45	1.03	0.22
7	0.27	0.99	0.24	0.63	0.42	0.87	0.22
8	0.3	1.02	0.23	0.26	0.4	0.72	
9	0.25	0.83	0.24	0.46	0.64	0.64	
10	0.25	0.73	0.21	0.46	0.72	0.72	
AVER	0.297	1.07	0.27	0.543	0.551	0.936	0.2425
SD	0.037133	0.204993	0.037118	0.127371	0.104078	0.19772	0.045
SEM	0.09392	0.064825	0.011738	0.040278	0.032912	0.062525	0.0225
N	10	10	10	10	10	10	4

	Distance				
		Root Wall Thickness			
BL		MB canal	ML canal	DB/D canal	DL canal
	1				
	2	1.47	1.71	1.83	
	3	1.4	1.43	1.7	
0.17	4	1.42	1.51	1.61	2.21
0.34	5	1.33	1.32	1.42	2.04
0.25	6	1.25	1.28	1.27	1.84
0.28	7	1.21	1.23	1.25	2.01
	8	1.08	1.06	1.18	
	9	1.04	1.18	1.23	
	10	0.91	0.86	1.18	
0.26		1.234444	1.286667	1.407778	2.025
0.070711		0.191775	0.2497	0.245956	0.151548
0.035355		0.063925	0.083233	0.081985	0.075774
4		9	9	9	4