CONE BEAM COMPUTED TOMOGRAPHY-ANATOMIC ANALYSIS OF MANDIBULAR POSTERIOR TEETH: IMPACT ON ENDODONTIC MICROSURGERY

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Dedication

To my precious family, for always supporting my efforts to grow in my educational pursuits, in spite of the 26 months spent apart and the 8 hours time difference.

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Abstract

Purpose: The purpose of this study was to use cone beam computed tomography (CBCT) measurements to investigate the root thickness (B-L) of the mandibular posterior teeth at the root end resection level, the thickness of the buccal and lingual bone at both the resection level and the mandibular canal (MC) level, the dimension of the mandibular canal, the relative location of the mandibular canal to the tooth, and the possible differences between males and females.

Methods: CBCT scans from 106 patients (ages 18-69) were used to evaluate measurements from 801 teeth and respective tooth areas. Bone and root thickness were measured at the preferred root resection level of 3mm from root apex, and at the level of the mandibular canal. Also, the dimension and the relative location of the mandibular canal (MC) to the apices of the posterior teeth were evaluated.

Results: Buccal bone was thinnest over the root of the 1st premolar (2.08 mm) and thickest over the distal root of the 2nd molar (6.35 mm). Bone thickness averaged 2.19 mm over the root of the 2nd premolar, 2.3 mm over the mesial root of the 1st molar, 3 mm over the distal root of the 1st molar, and 5.16 mm over the mesial root of the 2nd molar, respectively. Root thickness (B-L) at the resection level averaged 4.58mm, 5.42mm, 5.28mm, 5.77mm, 4.39 mm and 4.3mm for the

2nd molar distal root, 2nd molar mesial root, 1st molar distal root, 1st molar mesial root, 2nd premolar and 1st premolar, respectively. Mandibular bone thickness lingual to the root was more consistent, ranging from the thinnest area over the distal root of the 2nd molar (2.42 mm) to the thickest over the root of the 2nd premolar (4.5mm). The mandibular canal (MC) location in relation to the individual tooth roots was most often seen to the buccal in the area of the 2nd molar distal root (58%) while it was most often seen to the lingual of the root at the level of the mesial root of the 1st molar (31.5%). The MC was inferior to roots of posterior teeth in 38-58% of the time.

Conclusions: Knowledge of the mandibular posterior tooth dimension for apical resection is beneficial to the endodontist. The depth of the root below buccal bone, its relative position in the mandible as well as to the mandibular canal can aid the surgeon performing the root resection and this data contributes to a knowledge base for the practicing endodontist.

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INTRODUCTION

Tooth caries is the most extensive infectious disease in the world, and often results in infected pulp tissue requiring endodontic treatment. According to the AAE Colleagues for Excellence 2010 Spring Newsletter, "the ultimate goal of endodontic treatment is to create an environment in which the body can heal itself". [1] This goal can be achieved through "the endodontic triad", consisting of biomechanical preparation, microbial control and complete obturation of the canal system. [2] In cases that healing cannot be achieved through orthograde initial treatment or retreatment, a surgical procedure to resect the root end and seal the apical end of the tooth should be considered. Surgical endodontic procedures in these cases include root end resection with retrograde filling (root end filling), as well as apical curettage in order to remove the lesion and submit the removed specimen for biopsy.

Before surgery, it is imperative for the clinician to be familiar with the anatomical landmarks and structures adjacent to the area that the surgery will be performed, as well as tooth dimensions and anatomy. The buccal and lingual bone thickness, the dimensions and inclination of roots, and the adjacent anatomical structures, especially nerve location, are all critical factors in planning and performing the osteotomy and the root-end resection/root-end fill procedure.

Radiographic information is often used to help manage endodontic problems, from diagnosis and treatment to assessing outcome. The amount of information gained from conventional films and digitally captured periapical radiographs is limited by the fact that the three-dimensional anatomy of the area being radiographed is compressed into a two-dimensional image [3]. The application of small volume cone beam computed tomography (CBCT) imaging techniques aids in overcoming the aforementioned problem. When compared to anatomical studies using cadavers, CBCT has the advantages of non-invasiveness and providing a greater amount of information.

REVIEW OF THE LITERATURE

ENDODONTIC MICROSURGERY

Looking back in the history of dentistry, a Sumerian text in 5000 BC describes "tooth worms" as the cause of dental decay. The earliest known reference to a person identified as a dental practitioner is from 2600 BC in Ancient Egypt, when an inscription on Hesy-Ra's tomb acknowledged him as the first "dentist". Hippocrates and Aristotle wrote about the eruption pattern of teeth, treatment of decayed teeth and gum disease, extractions with forceps, and the use of wires to stabilize loose teeth and fractured jaws. In the middle ages priests or barbers performed dentistry, and it wasn't until 1841 when Alabama enacted the first dental practice act, regulating dentistry in the United States. (ADA, history of dentistry timeline) In 1910 Dr. William Hunter of London postulated the "Focal Infection Theory", regarding the Relation between Oral Infection and Systemic Disease, and woke the dental profession to its responsibilities.

Endodontic surgery has history in the field of dentistry. The first "endodontic surgery" was performed almost 2000 years ago, when an acute periapical abscess was treated by incision and drainage. More specifically, the oldest written account of a dental operation other than extraction is found in a statement by Archigenes of Rome, who advocated the trephination of a non-carious symptomatic tooth in order to evacuate it from the morbid material in the interior. Since then, the continuous technologic and scientific advancements in dentistry have allowed the clinician to treat cases effectively and efficiently that would otherwise be condemned to extraction.

The overall goal of endodontic treatment is to prevent or cure apical periodontitis and to retain the treated teeth in function. Despite the skills of the clinician, incomplete debridement, extraradicular infection, ledges, blockages, zips, perforations and separated instruments are common causes that might affect the outcome of orthograde treatment or retreatment. Unsuccessful attempts to non-surgically rectify these problems and persisting patient's symptoms are indications for a surgical approach. Moreover, aberrations and anatomical variations that are inaccessible, leaving areas undebrided by orthograde treatment or retreatment, can be addressed surgically. [4]

According to the American Association of Endodontists Colleagues for Excellence, "Asymptomatic Apical Periodontitis is inflammation and destruction of the apical periodontium that is of pulpal origin." Asymptomatic Apical Periodontitis does not manifest with clinical symptoms, but widening of the periodontal ligament or apical radiolucency is noted. Furthermore, the American Association of Endodontists Colleagues for Excellence defines that "Symptomatic Apical Periodontitis represents inflammation, usually of the apical periodontium, producing clinical symptoms involving a painful response to biting and/or percussion or palpation". [5] Radiographic changes, such as widening of the periodontal ligament or periapical radiolucency, may be noted, and that depends upon the stage of the disease. Severe percussion and/or palpation sensitivity is highly indicative of a degenerating pulp, and root canal treatment is indicated. [6]

Persistent apical periodontitis has been found in 14% of cases after initial therapy and in 18% of cases after orthograde retreatment. [7–9] In cases of persistent apical periodontitis, surgical endodontic therapy is indicated and should be presented as an option to the patient. Surgical endodontic therapy is also called apicoectomy or root-end resection/root-end fill (RER/REF).

During the 2007 Dental Pan-Society plenary session (a triennial joint meeting between the British Endodontic, Periodontic, Restorative and Prosthetic Dentistry Society), delegates were asked about the case management of a long-standing fixed partial bridge with failed endodontic treatment. The majority of the delegates favored extraction and prosthetic rehabilitation versus endodontic retreatment, which was in contrast to endodontists response of endodontic retreatment. Endodontic skill level may affect the decision significantly when planning treatment for complex restorative cases, but the endodontic microsurgery option should be presented to the patient even if referral is needed. [10]

Historically, apical surgery was limited to anterior teeth, because of increased visibility and access. Magnification was seldom used, with the resection and the retropreparation of the canal performed using conventional handpieces. The root resection was performed with a steep bevel, and restorative materials were used to fill the root-end preparation (amalgam, IRM and Super EBA).

The introduction of the ultrasonic handpiece appeared to provide a significant advantage in the treatment of deeply fluted roots with an isthmus by reducing the risk of perforations, when compared to the conventional microhandpiece. [11] When used to prepare root-end cavities to bilaterally matched teeth, ultrasonic preparations were found to be significantly deeper, had a significantly smaller bevel angle, deviated less from the canal, and required a significantly smaller osteotomy, when compared to high-speed bur preparations. [12] Also, when used to prepare root end cavities in endodontically treated, resected roots in human cadavers, ultrasonics used in low to moderate power settings, did not cause root dentin microfractures. [13]

The introduction of the dental operating microscope is a strong contributor to the advancement of surgical endodontics. This would allow the clinician to reduce the osteotomy size and perform the resection with a minimal or zero degree bevel. A 1 mm resection reduces 52% of the apical ramifications and 40% of the lateral canals, a 2mm resection reduces these by 78% and 86%, respectively, and a 3 mm resection eliminates 93% of apical ramifications and 98% of the lateral canals. [14] Except for the root length that needs to be resected, the bevel of the resection plays an important role in the surgical outcome, with a minimal or zero degree bevel resection significantly decreasing the apical leakage. [15,16] In a study that compared the traditional technique (root-end resection with a 45 degree bevel angle, and retrograde preparation with a carbide round bur) to the modern technique (root-end resection with minimal or no bevel, and retrograde preparation using ultrasonic retro-tips with the aid of a dental operating microscope), successful healing was only 44.2% compared to a 91.1% using the modern technique. [17]

Moreover, a recent meta-analysis of the literature showed that the outcomes obtained using a microscope were associated with significantly better outcomes than loupes. Between the retrofill materials, MTA was found to be superior to gutta-percha and amalgam, but not when compared to IRM. The combined use of an operative microscope and MTA is associated with better outcomes, when compared to other magnification devices or other retrofilling materials. [18]

ANATOMICAL LANDMARKS WHEN CONSIDERING ENDODONTIC SURGERY - INFERIOR ALVEOLAR NERVE AND MENTAL FORAMEN LOCATION

An important aspect of our preoperative assessment is the location of anatomical landmarks that may be disrupted within the surgical field such as the sinus, the nasal floor, the inferior alveolar, mental, and incisive nerve, and the palatal artery. The inferior alveolar nerve (IAN) location is an important consideration when performing endodontic surgery in the mandibular premolar and molar area.

The IAN has a close proximity to the apices of the teeth. Different studies have investigated the distance between the IAN and the apices of the teeth using various methodologies. Denio et al. sectioned dried mandibles through the root apices of the mandibular premolars and molars, and found that the apices of the mesial roots of the first molars were farthest from the canal with a mean distance of 6.9 mm. Second premolars and second molars had the closest distances to the canal with a mean of 4.7 mm and 3.7 mm, respectively. The canal pathway in mature mandibles followed an S-shaped curve in 31% of the cases, and was located lingually 19%, buccally 17%, or directly inferior to the apices 5% of the time. [19]

Littner et al. also evaluated dry mandibles by taking radiographs of the molar areas utilizing the paralleling technique, and an additional radiograph at −20° angulation of the same area. The distance between the upper border of the mandibular canal and the root apices of the first and second molars were measured, and the location of the mandibular canal in the buccolingual plane was determined. The mandibular canal was more commonly found buccally to the apices of the second molar; in the first molar area the canal was lingual to the root apices in almost 50% of the cases. The distance between the upper border of the mandibular canal and the apices of the molars was ranging from 3.5 to 5.4 mm. The authors stated that in no case was the mandibular canal found in close proximity to the first and second molar apices, both in the vertical and in the buccolingual planes. [20]

Another method to examine the course of the mandibular canal and its distance from the apices of the posterior teeth is by evaluating CBCT scans. Cone beam computed tomography has an important role in detailed “mapping” of the posterior mandible, because it is an accurate, noninvasive method to evaluate the proximity of the apices of teeth to the inferior alveolar canal. Kovisto et al. did a retrospective CBCT study to investigate the proximity of the mandibular canal to the tooth apex, and found that the second premolar was the farthest away from the mandibular canal, and the distal root of the second molar was closest to the mandibular canal, with an average distance of 2.64 mm and 1.42 mm, respectively. [21]

In a study done by Ludlow et al., distances between anatomic points and reference wires were measured by using panoramic reconstructions (two-dimensional) and direct measurements from axial slices (three-dimensional) of cone beam computed tomography volumes of 28 skulls in ideal, shifted, and rotated positions. The average error was less than 1.2% and 0.6% for two-dimensional and three-dimensional measurement techniques, respectively, and CBCT measurements were not significantly influenced by variation in skull orientation during image acquisition. Thus, CBCT imaging of the skull anatomy can provide more accurate information for the mandibular canal anatomy and its relative position to the teeth apices, even in cases with small image distortion. [22]

As reported in previous CBCT studies, the distance from the inferior alveolar nerve to the root apices can depend upon age and sex, with females demonstrating smaller distances than males, regardless of age, and with the distal roots being closer to the nerve than mesial roots for both males and females. Kovisto et al. found no sex difference in the distance from root apices to the mandibular canal for age <48. For female subjects older than 48 years old, the mesial and distal roots of the second molar were found to be closer to the mandibular canal than in male subjects of the same age. [21] Another study stated that the distance between the inferior alveolar nerve and mandibular first molar roots depends upon the age and gender, with shorter distances for females than males, and for subjects aged 16-25 years and >55 years than in other age groups. [23] The overall width of the mandible decreases from the 3rd–6th decade of life in both genders, however the position of the nerve within the mandible seems to be age-nonrelated, and appears similar between both genders. [24]

The inferior alveolar nerve can be damaged during many dental procedures, including administration of local anesthetic [25], implant site preparation and placement [26] [27], non-surgical [28–31] and surgical endodontic therapy [32,33], third molar surgery and other surgical interventions. [34] Damage to sensory nerves can result in anesthesia, paresthesia, dysesthesia, or pain, which will all cause sensory and functional impairment to the patient. Many of these iatrogenic nerve injuries can be avoided with thorough preoperative assessment. Renton et al. evaluated patients with nerve injury following 3rd mandibular molar surgery, and found that the injury involved the inferior alveolar nerve in 44.2% of the cases and the lingual nerve in 55.8% of the cases. Neuropathy was demonstrable in all patients with varying degrees of paresthesia, dysesthesia (in the form of burning pain), allodynia and hyperalgesia, and female patients had higher occurrence of IAN and lingual nerve injuries.

Neurosensory impairment of the inferior alveolar nerve can also occur when non-surgical endodontic therapy is performed on the mandibular posterior teeth. The possible mechanisms associated with IAN injury are: mechanical trauma from overinstrumentation into the inferior alveolar canal, a pressure phenomenon from the extrusion of endodontic intracanal or obturation materials within the inferior alveolar canal, or a neurotoxic effect from the intracanal medicaments, irrigation solutions and obturation materials. [35] These potential endodontic misadventures, as well as the increased use of implants, can lead to nerve damage. Invasive dental procedures are the etiologic factor in 63% of cases with neuropathy. [36]

As seen below in *Figure 1*, intracanal medicament ($Ca(OH)_2$) has been expressed out of the tooth and into the mandibular canal, causing the patient pain and a surgical procedure was necessary to decompress the inferior alveolar nerve and remove the material.

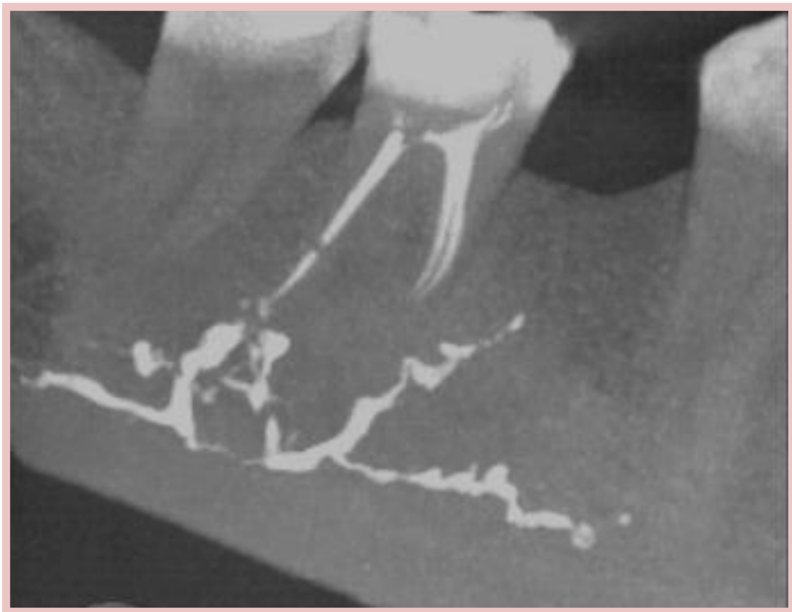

Figure 1. Intracanal medicament ($Ca(OH)_2$) expressed into the mandibular canal

The likelihood of post-operative discomfort following endodontic surgery is common. In a follow-up of 1107 dentoalveolar operations in the postcanine region, temporary sensitivity disturbances of the inferior alveolar and the lingual nerve were found at 2.2% and 1.4% of the patients, respectively. [37] The incidence depended on the different surgical interventions performed, and the disturbances were completely resolved by 6 months. Even though the incidence of the IAN disturbances associated with apical surgeries in the postcanine region was as small as 0.8%, the clinician has to be aware of the location of the anatomical structures associated with the surgical field.

The mental foramen (MF) is another important landmark to consider during surgical endodontic procedures. Different technologies have been used to help operators determine the clinical location of the MF. Most of the techniques have their downsides, such as anatomical structures overlap, image distortion, magnification, radiation, and cost. [38] According to a classic study by Phillips, the mental foramen is most commonly found inferior to the second premolar and approximately 60% of the distance from the buccal cusp tip of the second premolar to the inferior border of the mandible. [39] The mental foramen appears slightly larger (23% increase in size of the mandibles examined) on panoramic radiographs than on periapical radiographs, and can be seen on 75% of the horizontal periapical radiographs examined. [40,41]

Moiseiwitsch has suggested three clinical stages during mandibular endodontic surgery, where potential damage to the neurovascular bundle exiting the mental foramen may be reduced (preoperative diagnosis, flap design and retraction): 1) a vertical PA using a paralleling device instead of a panoramic radiograph can provide more accurate information for the location of the mental foramen, 2) a triangular flap with a distal vertical releasing incision is the flap of choice, and 3) a groove in the bone superior to the foramen can prevent retractor slippage. [42]

Accessory innervation, such as the accessory mental foramina and accessory branches of the inferior alveolar nerve, can be damaged during periapical surgery. In a retrospective limited field CBCT study, the accessory mental foramina were present in 16 out of the 150 patients. Confirmation of the existence of the accessory MF could avoid nerve injury during periapical surgery. [43]

The emergence pattern of the mental nerve, as it is exiting the mental foramen, usually is in a superior and posterior direction called the “anterior loop”. Limited cone-beam computed tomography is depicting more precisely the "anterior loop" compared to panoramic radiography. Innervation of the soft tissues of the chin, lower lip, facial gingiva and mucosa in the anterior mandible rises from three to four branches that the mental nerve forms, exiting the mental foramen. The clinician needs to keep a safety distance when intervening surgically in the vicinity of the mental foramen, in order to avoid post-surgical neurosensory impairments and deficits. [44,45]

CONE BEAM COMPUTED TOMOGRAPHY

The use of cone-beam computed tomography (CBCT) in clinical endodontics is a powerful tool toward diagnosis, prognosis, treatment planning and follow-up. [46] Since the first CBCT unit was approved and introduced in dentistry in the United States in 2000 [47,48], numerous endodontic applications have been described in the literature.

A classic study by Bender & Seltzer highlighted the fact that periapical lesions cannot be detected predictably if they are confined to the cancellous bone. [49,50] Small volume CBCT is a three-dimensional imaging system that overcomes this limitation. Ex vivo [51] and in vivo [52] studies have demonstrated that CBCT can detect periapical lesions with a greater accuracy than periapical radiography. The classical Periapical Index (PAI) score, developed by Orstavik, aided in determining the periapical status of teeth on periapical radiographs. [79] However, with the advent of CBCT, there was a not a standardized system to evaluate periapical status of teeth using CBCT.

The CBCT PAI score, introduced by Estrela et.al, is a 6-point (0–5) scoring system calculated from determining the largest lesion measurement in either the buccolingual, mesiodistal, or diagonal dimension and taking into account expansion and destruction of cortical bone. When CBCT PAI score was applied to 1,014 images (periapical and high resolution CBCT images), it was found that CBCT detected 54.2% more periapical lesions than conventional radiography. [53]

Another limitation of conventional radiographs is the compression of a three-dimensional anatomy into a two-dimensional image, which in combination with geometric distortion and noise, result in misdiagnosis or underestimation of the size of existing periapical pathosis. Moreover, periapical and panoramic radiographs provide diagnostic information for the mesiodistal plane, but they do not allow for appreciation of the buccolingual dimension or the superimposition of adjacent anatomical structures. [47]

Overcoming the aforementioned limitations, CBCT can be used for assessment and treatment planning of traumatic dental injuries [54] [55], assessment of root fractures [56], presurgical anatomic assessment of teeth and adjacent anatomical structures [43], treatment planning for tooth anomalies such as dens invaginatus [57], and assessment of internal and external root resorption. [58]

Comparative studies have shown CBCT to be more accurate than conventional periapical radiographs in measurement of the length of endodontic obturation. [59] Likewise, the diagnosis of resorption, periapical bone defects [51], root fractures [56], and perforations [60] is more accurate using CBCT when compared to periapical radiography.

Comparison of radiation doses of common dental examinations with a chest radiograph reveals that that the equivalent number of chest films is 0.13 for 1 PA or BW, 1.3-2 for a full mouth series, and 0.2 for a panoramic radiograph. [61] High-resolution limited CBCT minimizes effective absorbed dose of radiation compared with the traditional spiral computed tomography. In a study done by Ludlow et.al, the effective doses were measured according to the 2007 International Commission on Radiological Protection (ICRP) recommendations, and ranged as follows: 68 to 1,073 microSv for Large-field of view (FOV) CBCT, 69 to 560 microSv for Medium-FOV, whereas a similar-FOV a scan using a 64-slice multidetector CT (MDCT) produced 860 microSv. [62] CBCT dose varies substantially depending on the device, FOV and selected technique factors. In a study comparing 3 CBCT devices for oral and maxillofacial radiology (NewTom 3G, i-CAT and CB Mercuray), the calculated doses, according to the 2005 International Commission on Radiological Protection (ICRP) recommendations, were 59 microSv, 193microSv and 558microSv, respectively. These are 4 to 42 times greater than comparable panoramic examination doses. Reductions in dose were seen with reduction in field size and mA and kV technique factors. [63] Moreover, on a CBCT review study published by the American Association of Endodontists Colleagues for Excellence in 2011, the approximate ionizing radiation dosages were 4.7μSv, 9.8μSv, 38.3μSv and 20μSv for focused field anterior CBCT (Kodak), focused field maxillary posterior CBCT (Kodak), focused field mandibular posterior CBCT (Kodak), and 3D Accuitomo (J Morita), respectively. The dosage for 1 digital periapical radiograph was approximately 6μSv, as shown in *Table 1* below. [64]

Ionizing Radiation Dosages *(approximate)*

Activity	Effective Dose in μSv	Dose as Days of Equivalent Background Radiation
1 day background radiation, sea level	7-8	1
1 digital PA radiograph	6	1
4 dental bite-wing radiographs, F-speed film	38	5
FMX; PSP or F-speed film	171	21
Kodak® CBCT focused field, anterior	4.7	0.71
Kodak® CBCT focused field, maxillary posterior	9.8	1.4
Kodak® CBCT focused field, mandibular posterior	38.3	5.47
3D Accuitomo, J. Morita	20	3
NewTom 3G, ImageWorks	68	8
Chest x-ray	170	25
Mammogram	700	106
Medical CT, head	2,000	243
Medical Cat Scan (Spiral CT abdomen)	10,000	1,515
Federal Occupation Safety Limit per Year	50,000	7,575

Table 1. Ionizing radiation dosages (approximate)

The rising usage of CBCT imaging makes routine tests for dose estimation imperative, in order to prevent the patients and operating staff from excessive radiation exposure. The International Commission on Radiological Protection has recommended the use of diagnostic reference levels (DRLs), which are defined as an easily measureable quantity, usually the absorbed dose in air or in a tissue equivalent material at the surface of a simple standard phantom or representative patient. [65] The use of radiation-protective shielding minimizes radiation exposure of personnel and patients. Application of a thyroid collar around the front neck can reduce the total effective doses to 208.5 μSv (18.0% reduction), 149.1 μSv (40.1% reduction) and

110.5 μSv (38.7% reduction), for large, middle and small field of view (FOV), respectively. [66]

An important advantage of CBCT is the ability to acquire all data in a single pass. The X-ray source and detector rotate around a fixed fulcrum within the region of interest (ROI). During the exposure sequence hundreds of planar projection images are acquired of the field of view (FOV) in an arc of at least 180◦, with only one rotation of the gantry needed to acquire enough data for image reconstruction. [67]

Some of the disadvantages associated with CBCT imaging include noise and artifacts from endodontic filling materials (gutta-percha and sealer) and radiopaque restorations (amalgam, composite, crowns), the significantly higher cost of the software and hardware compared to the conventional PAs, higher doses of radiation, and CBCT availability in remote areas. Despite these disadvantages, CBCT imaging technology is becoming more available and popular among dental practices and patients.

OBJECTIVES

Knowledge of the mandibular posterior tooth dimension for apical resection is beneficial to the endodontist. The root thickness at the 3mm level (from the apex) and the tooth position relative to the mandibular canal, as well as the buccal and lingual bone thickness over the root, can aid the surgeon performing the root resection.

The objectives of this retrospective study were: to 1) measure the buccolingual (B-L) root thickness of the posterior teeth at the 3mm level from the apex (preferred level for root end resection), 2) evaluate the dimensions of the buccal and lingual bone over the root at the 3mm level from the apex, 3) measure the diameter of the mandibular canal (MC) and the buccal and lingual mandibular bone thickness over the canal at the mandibular canal level, 4) investigate the relative location of the mandibular canal (MC) to the apices of the posterior teeth, and 5) determine if sex differences affect any of the above measurements.

MATERIALS AND METHODS

The present study was approved by the Institutional Review Board at the University of Minnesota with number 1301M26223. CBCT scans (n=106) taken in 2012-2013 were collected from the University of Minnesota Oral and Maxillofacial Radiology using the Next Generation i-CAT® (Imaging Sciences, Hatfield, PA). i-CAT Vision software was used to evaluate the mandibular teeth and the adjacent anatomical structures.

The patients were either patients of record or referred from outside practices. The scans were obtained from a database pool of images taken for diagnostic purposes or presurgical evaluation, unrelated to the present study. Exclusion criteria for the study were: 1) more than one mandibular posterior tooth missing per side excluding third molars, 2) more than one mandibular anterior tooth missing, 3) significant periodontal disease/bone loss, 4) resorption of any mandibular tooth, and 5) artifacts of any kind impeding identification of anatomic structures. C-shaped mandibular molars were included in the study for the evaluation of the buccal and lingual bone thickness over the apices, but were excluded when the average root thickness (at the 3mm from the apex level) was calculated. 8 scans had a field of view (FOV) of 170mm with 0.3mm resolution, 62 had a FOV of 130mm with 0.25mm resolution, and 36 had a FOV of 60mm with 0.2mm resolution.

The CBCT scans were evaluated by two graduate endodontic residents and one dental student. The examiners were calibrated for radiographic interpretation of the scans. The scans were viewed and evaluated on a Dell 24-inch non-glossy monitor with a

Dell Optiplex 9010 WorkStation (Dell Inc, Round Rock, TX), using the i-CAT Imaging System Software (i-CAT, Imaging Software Sciences International Inc, Hartfield, PA). The examiners had the ability to magnify the images, and change the viewing settings, such as density, contrast and sharpness, in order to enhance visibility and identification of the examined structures. Cross-sectional slices from the "implant screen" view mode were used to complete all the measurements at the radiographic apex of each mandibular tooth present, as well as the measurements of the mandibular canal diameter and position. The software allowed recording of linear measurements of the CBCT slices with a resolution range of 0.2mm to 0.3mm.

In order to perform the measurements at the 3mm from the apex level (optimal level for root end resection), a line was drawn along the long axis of the tooth, extending from the radiographic apex to 3mm coronally (red line on *Figure 2*). Because of limitations related to image resolution, when the line drawn from the apex could not be exactly 3mm, the closest measurement was accepted. The range of the accepted measurements was between 2.93-3.09mm. A second line was drawn perpendicular to the first, and the three consecutive measurement/segments of that line represented the distance from the outer buccal cortex to the root (BC-RA), the buccal-lingual root thickness (RA), and the distance from the root to the outer lingual cortex (LC-RA), respectively. The examiners were able to use a protractor to verify that the line was drawn as close to 90° as possible.

The aforementioned measurements are represented in *Figure 2* by the blue, green and yellow line, respectively, and the red line represents the 3mm from the apex mark.

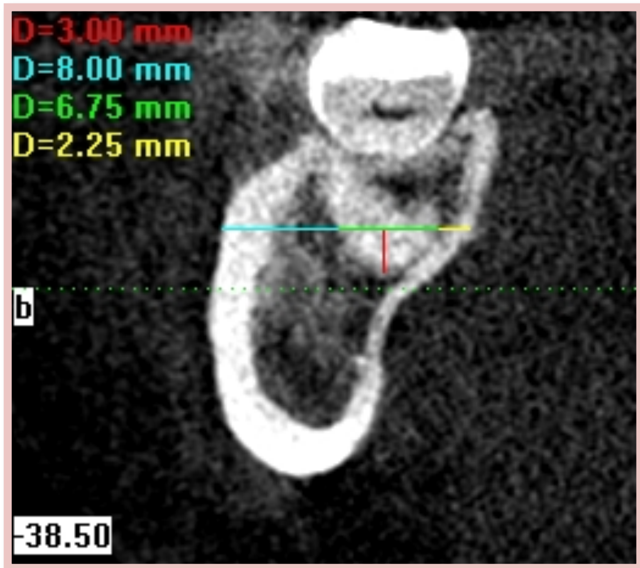

Figure 2. Measurements of the buccal and lingual bone thickness and dimension of the root at 3mm from the apex

The mandibular foramen was located and the inferior alveolar nerve was traced from its origin, in order to better identify the mandibular canal. The mandibular canal measurements included the distance between the mandibular canal and the buccal and lingual cortical plates, and the diameter of the canal.

The measurements were taken parallel to the Frankfurt horizontal line (green dotted line), as shown on *Figure 3*. For the mandibular canal measurements, a vertical line was drawn perpendicular to the Frankfurt horizontal line from the radiographic apex of the tooth to the height of the center of the canal. A second line was drawn perpendicular to the first, and the three consecutive measurement/segments of that line represented the distance from the outer buccal cortex to the buccal aspect of the mandibular canal (BC-MC), the mandibular canal diameter (MC dia), and the distance from the lingual aspect of the mandibular canal to the outer lingual cortex (LC-MC), respectively. The latter measurements are represented in *Figure 3* by the blue, green and yellow line, respectively.

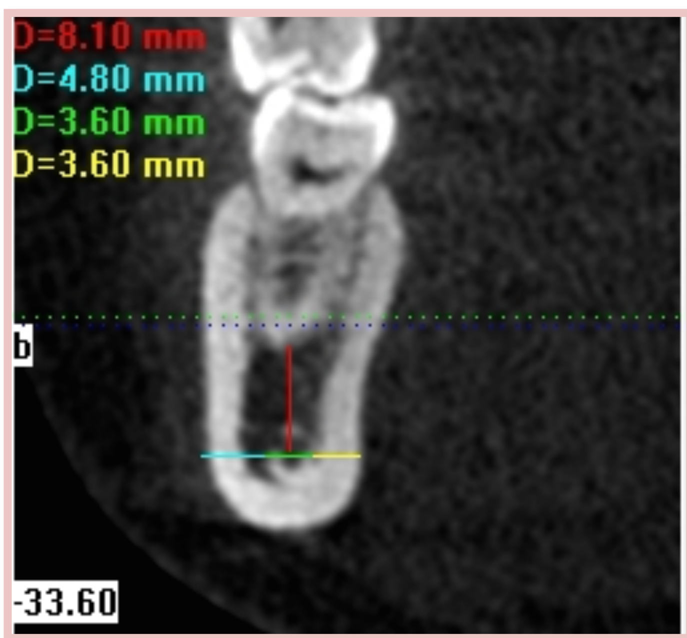

Figure 3. Measurements of the buccal and lingual bone thickness and mandibular canal diameter at the level of the mandibular canal

In order to evaluate the horizontal relationship of the tooth apex to the mandibular canal, the vertical relationship was determined first: a vertical line (red line in *Figure 4*) was drawn perpendicular to the Frankfurt horizontal line from the radiographic apex of the tooth to the height of the center of the canal. A second line was drawn perpendicular from this point to the center of the canal, and this measurement was recorded to determine if the mandibular canal was located inferiorly, bucally or lingually to the tooth apex. (*Figure 4*) The blue line in *Figure 4* represents this measurement. In order to be considered lingual or buccal, the canal must have been outside of a 3 mm diameter circle (the average diameter of the mandibular canal) placed directly below the apex.

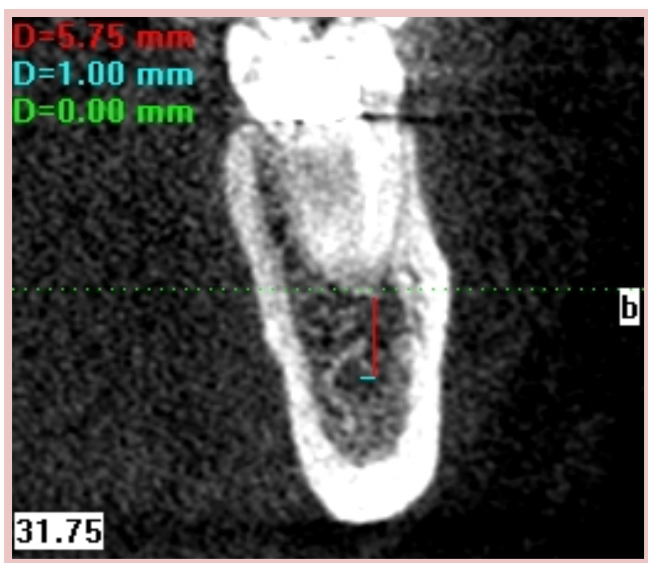

Figure 4. Relative position of the mandibular canal to the apices of the teeth

STATISTICAL ANALYSIS

The data were recorded using Microsoft Office Excel 2010 and statistically analyzed. Means and standard deviations were calculated for each measurement within each exam. Generalized estimating equations were used to compare measurements. Statistical significance was determined at $p \leq 0.05$. If the test for the overall tooth effect was $p \leq 0.05$, then pairwise comparisons were made. P values were adjusted for multiple comparisons using the Tukey method. Pearson correlation coefficients were calculated to compare the change in measurements with sex. Statistical analysis was performed with SAS software version 9.3 (SAS Institute Cary, NC)

RESULTS

CBCT scans (n=106) were used in this study for evaluation of 801 mandibular posterior teeth and associated areas in the mandible. The demographic analysis revealed that 68% of the study population was females (n=72) and 32% were males (n=34). The age of the study population ranged between 12 to 69 years old, with the mean age being 39.4 ± 16.0 years.

The mandibular canal could be identified in 105 out of the 106 scans for the mesial and distal root of the second mandibular molar. The most common images that the canal could not be identified were the mesial and distal roots of tooth #30. The number of present teeth/roots with an unidentifiable mandibular canal is presented in *Table 2*.

Tooth #/ Root	Unidentifiable MC	Tooth #/ Root	Unidentifiable MC
31 DR	1/106	**18 DR**	1/106
31 MR	1/106	**18 MR**	1/106
30 DR	5/106	**19 DR**	2/106
30 MR	6/106	**19 MR**	2/106
29	4/106	**20**	4/106
28	3/106	**21**	4/106

Table 2. Number of present teeth/roots with an unidentifiable MC

As mentioned in the exclusion criteria, the scans were not included in the study if more than one mandibular posterior tooth were missing per side (excluding third molars). Based on the results of the study, the most common missing tooth was the left first molar (n= 14), followed by the right first molar (n=12). The numbers of missing teeth for the rest of the posterior mandibular dentition were as follows: 6 right first premolars, 5 left first and 5 left second premolars, 2 left second premolars, 2 left second molars and 1 right second molar.

C-shaped mandibular second molars were noted with the same frequency on the left and right quadrants, numbering 6 out of the 104 left and 6 out of the 105 right mandibular second molars, respectively. In 4 out of 6 patients (66.7%) with C-shaped mandibular second molars, this canal configuration was noted bilaterally. These teeth were not included in the average root thickness measurements, since they only have a single root, but the buccal and lingual bone over the apices of the teeth was evaluated when estimating the average bone thickness.

The buccal and lingual cortical bone thickness measurements over the apex of each tooth/root, as well as the root thickness at the 3mm mark from the apex, for each individual tooth (left/right, first/second, premolar/molar) are presented in *Table 3*.

Tooth #/Root	Buccal cortex-root (BC-RA)	Root thickness (RA)	Lingual cortex-root (LC-RA)
31 DR Min	2.06	2.63	0.71
Max	9.96	6.49	6.21
Mean	6.57	4.46	2.32
31 MR Min	1.90	3.09	0.82
Max	10.00	7.25	5.94
Mean	5.39	5.30	2.68
30 DR Min	1.27	3.72	1.12
Max	7.99	7.00	8.25
Mean	3.18	5.19	4.02
30 MR Min	0.72	3.74	1.65
Max	6.36	7.60	9.93
Mean	2.53	5.54	4.20
29 Min	0.75	3.00	1.00
Max	5.84	6.05	8.79
Mean	2.38	4.30	4.30
28 Min	0.50	2.70	0.95
Max	4.75	6.73	8.81
Mean	2.05	4.34	4.26
21 Min	0.40	2.20	1.00
Max	5.10	6.60	7.50
Mean	2.11	4.26	4.16
20 Min	0.40	3.16	1.52
Max	5.77	7.04	8.00
Mean	1.99	4.49	4.71
19 MR Min	0.50	4.20	1.12
Max	5.80	8.78	8.40
Mean	2.08	5.99	4.47
19 DR Min	1.02	4.07	1.50
Max	7.54	7.89	7.95
Mean	2.83	5.37	4.27
18 MR Min	2.04	3.51	1.00
Max	9.00	8.00	6.82
Mean	4.93	5.54	2.92
18 DR Min	2.72	3.00	0.40
Max	10.82	7.25	6.43
Mean	6.13	4.69	2.52

Table 3. Measured distances at the 3mm from the apex level for each individual tooth/root

The measurements for the buccal and lingual cortical bone thickness and the root thickness at the 3mm mark from the apex, categorized for each tooth/root type (first/second, premolar/molar, mesial/distal root), are presented in *Table 4.*

Tooth #/Root	Buccal cortex-root (BC-RA)	Root thickness (RA)	Lingual cortex-root (LC-RA)
1st premolar			
Min	0.40	2.20	0.95
Max	5.10	6.73	8.81
Mean	2.08	4.30	4.21
2nd premolar			
Min	0.40	3.00	1.00
Max	5.84	7.04	8.79
Mean	2.19	4.39	4.50
1st molar MR			
Min	0.50	3.74	1.12
Max	6.36	8.78	9.93
Mean	2.30	5.77	4.33
1st molar DR			
Min	1.02	3.72	1.12
Max	7.99	7.89	8.25
Mean	3.00	5.28	4.15
2nd molar MR			
Min	1.90	3.09	0.82
Max	10.00	8.00	6.82
Mean	5.16	5.42	2.80
2nd molar DR			
Min	2.06	2.63	0.40
Max	10.82	7.25	6.43
Mean	6.35	4.58	2.42

Table 4. Measured distances at the 3mm from the apex level for each tooth/root type

It can be assumed from the table above that the more posterior the tooth is located within the arch, the thicker the buccal bone that needs to be removed in order to complete the buccal osteotomy. (*Figure 5*) The buccal bone thickness decreased from the second molar to the premolars area, averaging 6.35mm and 5.16mm for the second molar distal (DR) and mesial (MR) root, 3.00mm and 2.30mm for the first molar distal (DR) and mesial (MR) root, 2.19mm for the second and 2.08mm for the first premolar, respectively. The buccal bone thickness over the resection level ranged from 2.06mm to 10.82mm with an average of 6.35mm, and from 1.90mm to 10mm with an average of 5.16mm, for the distal and mesial root of the second molar, respectively. The buccal bone thickness measurements for the second molar mesial and distal roots were found to be statistically significant compared to all the other posterior teeth/roots dimensions.

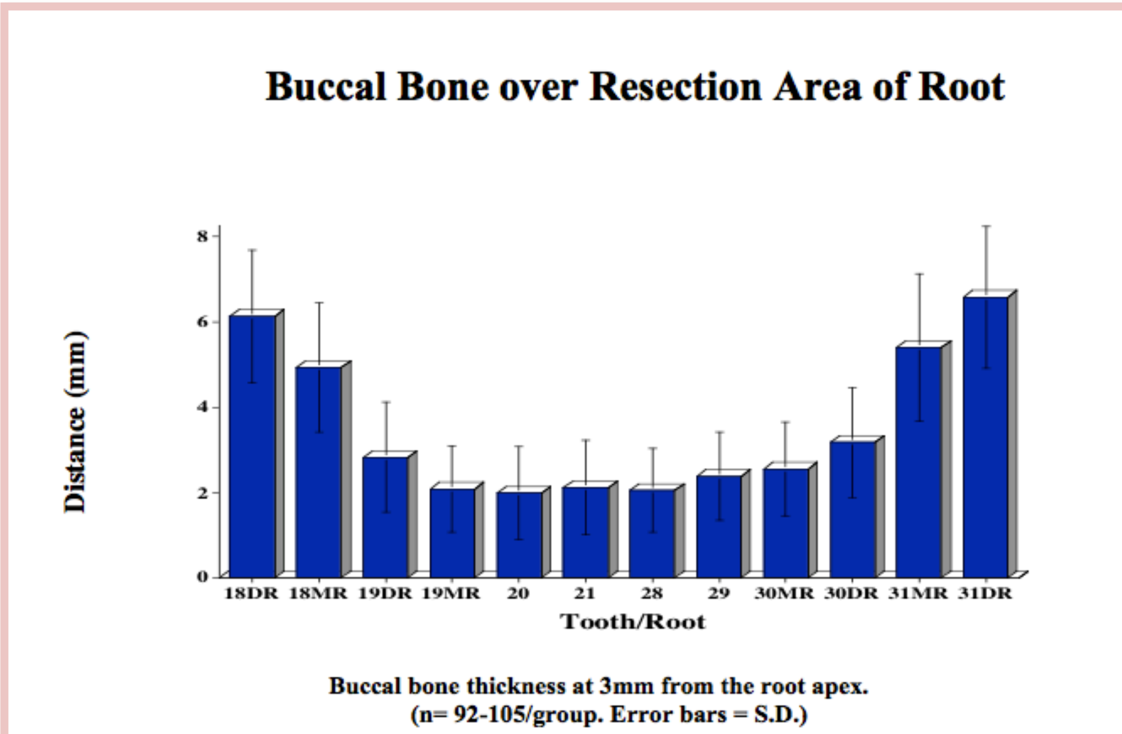

Figure 5. Buccal bone thickness over the resection level (3mm from the apex)

The lingual bone thickness increased from the second molar to the premolars area, averaging 2.42mm and 2.80mm for the second molar distal (DR) and mesial (MR) root, 4.15mm and 4.33mm for the first molar distal (DR) and mesial (MR) root, 4.50mm for the second and 4.21mm for the first premolar, respectively. (*Figure 6*)

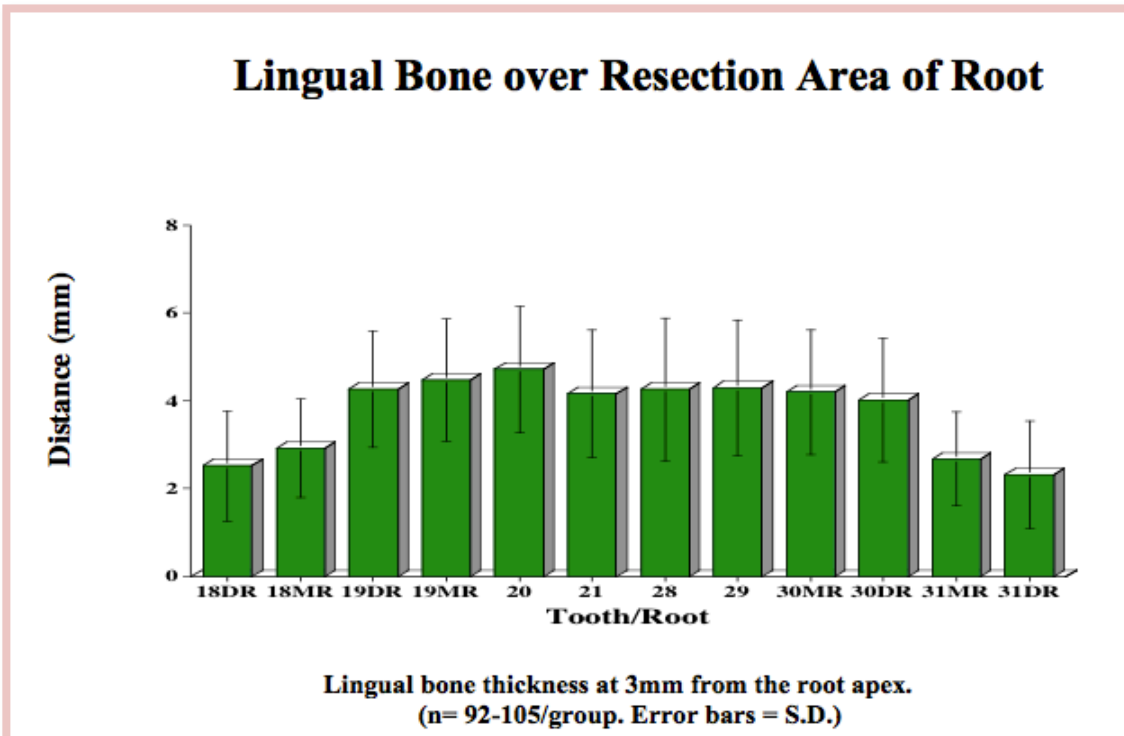

Figure 6. Lingual bone thickness over the resection level (3mm from the apex)

As for the root dimensions at the root end resection level (3mm from the apex), the mesial root of the first molar (R & L) demonstrated the largest root thickness, with an average of 5.77mm, followed by the mesial root of the second molar with an average of 5.42mm. The distal root of the first and second molar, the second premolar and the first premolar thickness averaged 5.28mm, 4.58mm, 4.39mm and 4.30mm, respectively. (*Figure 7*)

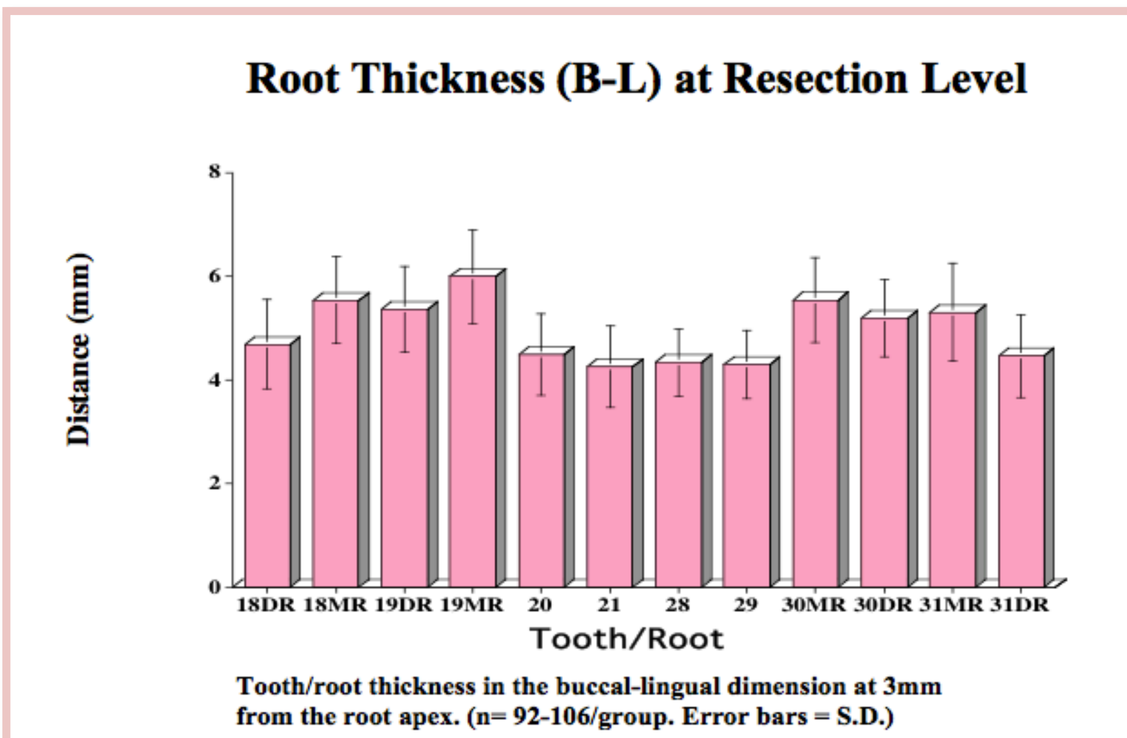

Figure 7. Root thickness at the resection level (3mm from the apex)

The average measurements for each individual tooth/root categorized by sex are demonstrated in *Table 5*, followed by the average measurements for each tooth/root type categorized by sex in *Table 6*. No significant differences between males and females were noted.

Tooth #/Root		**Buccal cortex-root (BC-RA)**	**Root thickness (RA)**	**Lingual cortex-root (LC-RA)**
31 DR	**males**	6.68	4.68	2.50
	females	6.53	4.37	2.25
31 MR	**males**	5.21	5.67	2.98
	females	5.47	5.14	2.54
30 DR	**males**	3.56	5.19	4.21
	females	2.98	5.20	3.92
30 MR	**males**	2.91	5.58	4.24
	females	2.36	5.53	4.18
29	**males**	2.65	4.48	4.23
	females	2.26	4.22	4.33
28	**males**	2.47	4.40	4.40
	females	1.83	4.31	4.19
21	**males**	2.57	4.20	4.40
	females	1.88	4.30	4.04
20	**males**	2.23	4.65	4.65
	females	1.88	4.42	4.74
19 MR	**males**	2.50	6.26	4.18
	females	1.93	5.90	4.58
19 DR	**males**	3.27	5.50	4.16
	females	2.66	5.32	4.31
18 MR	**males**	4.82	5.62	3.08
	females	4.98	5.51	2.85
18 DR	**males**	6.17	4.78	2.78
	females	6.11	4.65	2.41

Table 5. Average measured distances at the 3mm from the apex level for each individual tooth/root categorized by sex

Tooth #/Root		Buccal cortex-root (BC-RA)	Root thickness (RA)	Lingual cortex-root (LC-RA)
1st premolar	males	2.52	4.30	4.40
	females	1.86	4.31	4.12
2nd premolar	males	2.44	4.57	4.44
	females	2.05	4.32	4.52
1st molar MR	males	2.71	5.92	4.21
	females	2.15	5.72	4.38
1st molar DR	males	3.42	5.35	4.19
	females	2.82	5.26	4.12
2nd molar MR	males	5.02	5.65	3.03
	females	5.23	5.33	2.70
2nd molar DR	males	6.43	4.73	2.64
	females	6.32	4.51	2.33

Table 6. Average measured distances at the 3mm from the apex level for each tooth/root type categorized by sex

The measurements for the buccal and lingual cortical bone thickness over the mandibular canal, as well as the mandibular canal diameter measurements, taken as demonstrated in *Figure 3*, are presented in *Table 7*.

Tooth #/Root	**Buccal cortex-mandibular canal (BC-MC)**	**Mandibular canal diameter (MC)**	**Lingual cortex-mandibular canal (LC-MC)**
31 DR Mean	5.39	3.03	1.94
SD	1.53	0.60	0.96
31 MR Mean	5.45	2.97	1.94
SD	1.53	0.57	1.06
30 DR Mean	5.15	2.79	1.65
SD	1.33	0.57	0.79
30 MR Mean	4.49	2.88	2.01
SD	1.37	0.56	1.06
29 Mean	2.69	2.91	3.82
SD	1.49	0.76	1.80
28 Mean	3.06	2.53	4.22
SD	1.35	0.61	2.38
21 Mean	3.22	2.66	3.99
SD	1.27	0.73	2.17
20 Mean	2.68	3.08	3.87
SD	1.31	0.87	1.78
19 MR Mean	4.13	3.06	2.28
SD	1.41	0.66	1.16
19 DR Mean	4.68	2.98	1.77
SD	1.28	0.64	0.97
18 MR Mean	5.22	2.98	2.14
SD	1.52	0.60	1.24
18 DR Mean	5.11	3.07	2.28
SD	1.53	0.72	1.24

Table 7. Measured distances for the mandibular canal for each individual tooth/root

The measurements for the buccal and lingual cortical bone thickness over the mandibular canal, as well as the mandibular canal diameter measurements, categorized for each tooth type (first/second, premolar/molar), are presented in *Table 8*.

Tooth #/Root	Buccal cortex-mandibular canal (BC-MC)	Mandibular canal diameter (MC)	Lingual cortex-mandibular canal (LC-MC)
1st premolar			
Min	0.00	1.00	1.00
Max	6.25	6.25	9.25
Mean	2.67	3.00	3.85
2nd premolar			
Min	0.75	1.00	0.50
Max	7.80	5.00	16.25
Mean	3.14	2.60	4.11
1st molar MR			
Min	1.20	1.50	0.50
Max	8.00	4.50	5.80
Mean	4.31	2.97	2.15
1st molar DR			
Min	1.40	1.50	0.50
Max	8.00	4.75	5.60
Mean	4.92	2.89	1.71
2nd molar MR			
Min	0.80	1.50	0.50
Max	9.50	4.25	8.25
Mean	5.34	2.98	2.04
2nd molar DR			
Min	0.75	1.75	0.50
Max	9.75	5.00	6.75
Mean	5.25	3.05	2.11

Table 8. Measured distances for the mandibular canal (mm) for each tooth/root type

The average measured distances for the buccal and lingual bone thickness over the mandibular canal, as well as the diameter of the mandibular canal, for each individual tooth/root categorized by sex are presented in *Table 9* and *Figures 8, 9 and 10*.

Tooth #/Root		**Buccal cortex-mandibular canal (BC-MC)**	**Mandibular canal diameter (MC)**	**Lingual cortex-mandibular canal (LC-MC)**
31 DR	**males**	5.74	2.94	1.83
	females	5.24	3.07	1.99
31 MR	**males**	5.77	2.88	1.82
	females	5.30	3.01	1.99
30 DR	**males**	5.29	2.87	1.62
	females	5.07	2.75	1.67
30 MR	**males**	4.56	2.88	2.43
	females	4.46	2.88	1.81
29	**males**	2.97	3.02	3.84
	females	2.56	2.85	3.81
28	**males**	3.09	2.69	4.67
	females	3.05	2.44	4.00
21	**males**	3.32	2.58	3.98
	females	3.16	2.71	4.00
20	**males**	2.63	3.22	3.96
	females	2.71	3.01	3.83
19 MR	**males**	4.09	3.10	2.18
	females	4.15	3.05	2.32
19 DR	**males**	4.80	2.84	1.74
	females	4.64	3.03	1.78
18 MR	**males**	5.36	3.12	1.94
	females	5.15	2.92	2.23
18 DR	**males**	5.16	3.31	2.17
	females	5.09	2.97	2.33

Table 9. Average measured distances for the mandibular canal (mm) for each individual tooth/root categorized by sex

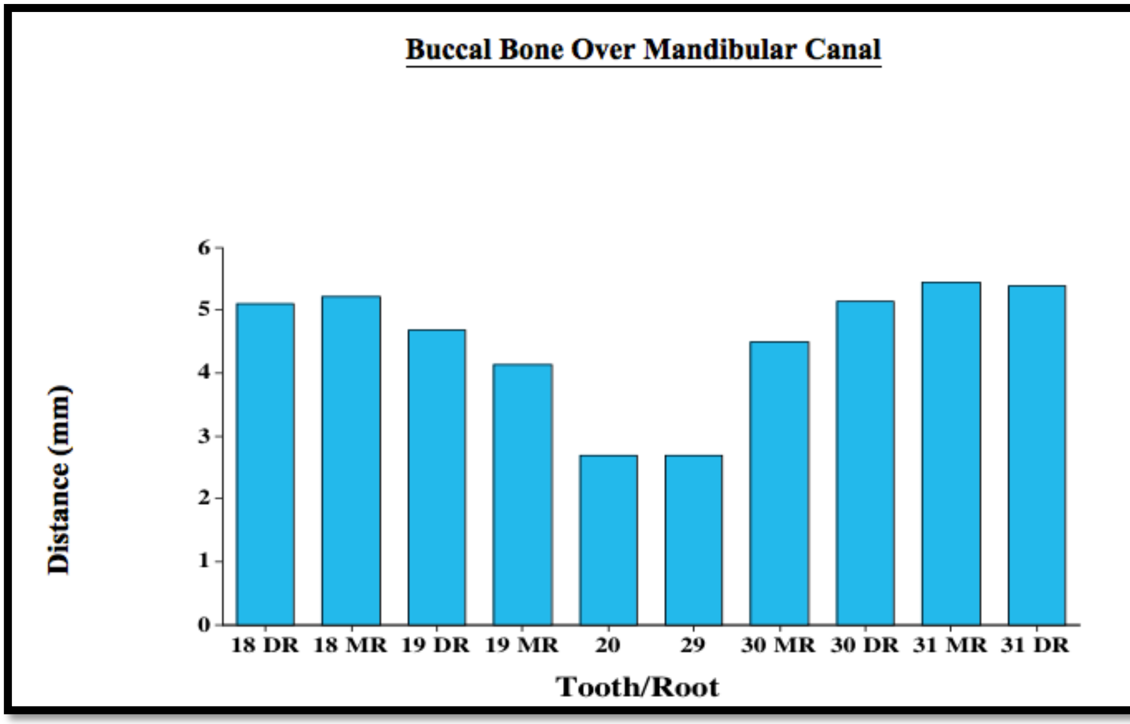

Figure 8. Buccal bone thickness over the mandibular canal

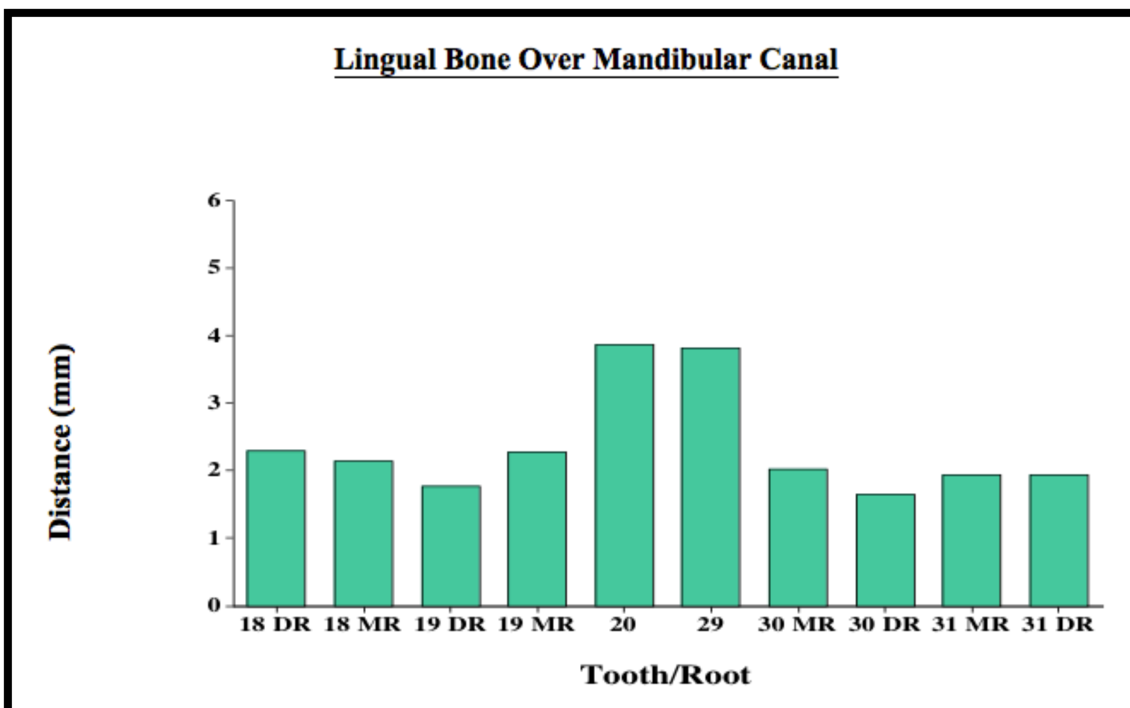

Figure 9. Lingual bone thickness over the mandibular canal

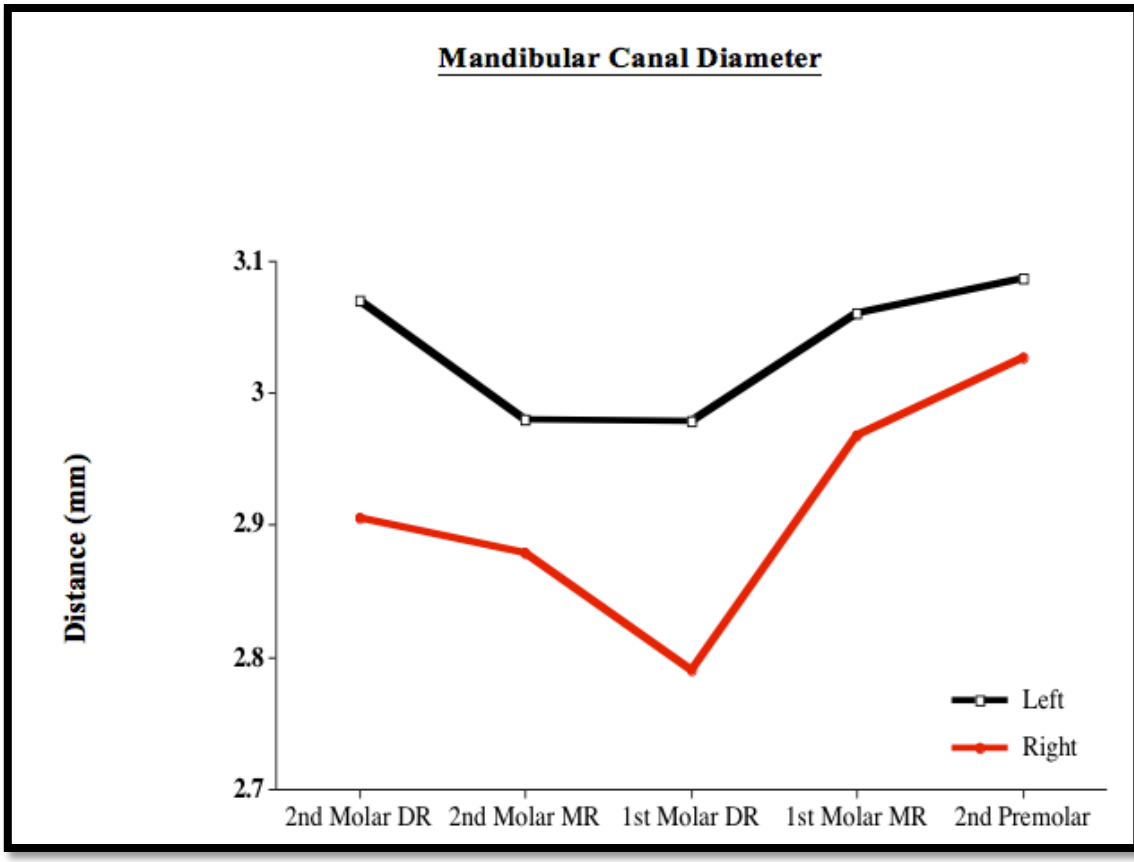

Figure 10. Mandibular canal diameter

From *Figure 8*, we can see that the buccal bone over the mandibular canal was thickest at the mesial root of the 2nd molars and thinnest over the 2nd premolar, averaging 5.4 mm and 2.6 mm, respectively. As far as the lingual bone thickness, as presented in *Figure 9*, the lingual bone over the mandibular canal was thickest over the 2nd premolar and thinnest at the distal root of the 1st molars (3.8 mm vs. 1.7 mm). The average diameter of the mandibular canal along the length of the canal from 2nd molar to 2nd premolar was 3.03 mm on the left and 2.91 mm on the right, as presented in *Figure 10*.

When combining both left and right lower quadrants, the average measured distances for the buccal and lingual bone thickness over the mandibular canal, as well as the diameter of the mandibular canal, for each tooth/root type categorized by sex are presented in *Table 10*. No significant differences between males and females were noted.

Tooth #/Root		Buccal cortex-mandibular canal (BC-MC)	Mandibular canal diameter (MC)	Lingual cortex-mandibular canal (LC-MC)
1st premolar	males	3.21	2.64	4.33
	females	3.11	2.58	4.00
2nd premolar	males	2.80	3.12	3.90
	females	2.64	2.93	3.82
1st molar MR	males	4.33	2.99	2.31
	females	4.31	2.97	2.07
1st molar DR	males	5.05	2.86	1.68
	females	4.86	2.89	1.73
2nd molar MR	males	5.57	3.00	1.88
	females	5.23	2.97	2.11
2nd molar DR	males	5.45	3.13	2.00
	females	5.17	3.02	2.16

Table 10. Average measured distances for the mandibular canal (mm) for each tooth/root type categorized by sex

The mean mandibular thickness at the resection level is calculated by adding the corresponding average measurements for the buccal and lingual bone thickness over the roots and the mean root thickness. Likewise, the mean mandibular thickness at the level of the mandibular canal is calculated by adding the corresponding average measurements for the buccal and lingual bone thickness over the canal plus the average canal diameter. The mean mandibular thickness for each individual tooth/root is presented in *Table 11*, and the mean mandibular thickness for each tooth/root type is presented in *Table 12*.

Mean mandibular thickness	#31 DR	#31 MR	#30 DR	#30 MR	#29	#28
3mm from the apex level	13.35	13.37	12.39	12.27	10.98	10.65
Mandibular canal level	10.36	10.35	9.59	9.38	9.42	9.81
	#18 DR	**#18 MR**	**#19 DR**	**#19 MR**	**#20**	**#21**
3mm from the apex level	13.34	13.39	12.47	12.54	11.19	10.53
Mandibular canal level	10.47	10.34	9.43	9.45	9.63	9.87

Table 11. Mean mandibular thickness (mm) for each individual tooth/root

Mean mandibular thickness	**1st premolar**	**2nd premolar**	**1st molar MR**	**1st molar DR**	**2nd molar MR**	**2nd molar DR**
3mm from the apex level	10.59	11.08	12.41	12.43	13.38	13.35
Mandibular canal level	9.52	9.85	9.43	9.52	10.36	10.41

Table 12. Mean mandibular thickness (mm) for each tooth/root type

It can be assumed from the two tables above that the mandibular thickness generally decreases as we move more anteriorly, both at the 3mm from the apex and at the mandibular canal level. Moreover, the mandibular thickness is greater at the 3mm from the apices level rather than at the level of the mandibular canal, demonstrating the bone distribution in order to accommodate for the anchorage of the teeth in the alveolar ridges.

The mean mandibular thickness for each tooth/root type at the resection and the mandibular canal level categorized by sex is presented on *Table 13*.

Tooth #/Root		**3mm from the apex level**	**Mandibular canal level**
1st premolar	**males**	11.23	10.16
	females	10.27	9.71
2nd premolar	**males**	11.44	9.82
	females	10.93	9.39
1st molar MR	**males**	12.84	9.62
	females	12.24	9.32
1st molar DR	**males**	12.95	9.58
	females	12.20	9.47
2nd molar MR	**males**	13.69	10.45
	females	13.25	10.30
2nd molar DR	**males**	13.80	10.58
	females	13.16	10.35

Table 13. Mean mandibular thickness (mm) for each tooth/root type at the 3mm from the apex and the mandibular canal level categorized by sex

From the results demonstrated in *Table 13*, we can see that the mean mandibular thickness is greater for male subjects when compared to female subjects, and this applies for both the mandibular canal level and the 3mm from the tooth apex level.

The horizontal distance between the center of the mandibular canal and the tooth apex determines if the mandibular canal is located inferiorly, bucally or lingually to the tooth apex. In order to perform the statistical analysis, when the canal was located to the buccal it was marked as "+", and when located to the lingual it was marked as "-".
The measurements for each individual tooth/root are presented in *Table 14*.

	#31 DR	**#31 MR**	**#30 DR**	**#30 MR**	**#29**	**#28**
Mean	B 1.51	B 1.31	B 0.08	L 0.47	B 0.68	B 0.42
Max buccal	6.60	5.40	3.60	3.50	5.25	5.00
Max lingual	2.25	3.75	3.50	5.00	4.80	3.25
	#18 DR	**#18 MR**	**#19 DR**	**#19 MR**	**#20**	**#21**
Mean	B 1.95	B 1.81	L 0.10	L 0.40	B 0.59	L 0.07
Max buccal	6.25	8.25	4.00	4.00	4.60	3.75
Max lingual	2.25	2.60	4.00	4.80	4.00	3.75

Table 14. Mean horizontal distance (mm) between the center of the mandibular canal and the tooth apex; "B" indicates buccal and "L" indicates lingual

The relative position of the mandibular canal to each individual tooth/root is demonstrated in *Table 15* and in *Figure 11*, and the relative position of the mandibular canal to each tooth is demonstrated in *Table 16*. If the center of the mandibular canal was located directly under the apex of the tooth or within 1.5 mm buccally or lingually, its relative position was considered as "inferior". Likewise, if the center of the mandibular canal was located more than 1.5 mm to the buccal or lingual, its relative position was considered as "buccal" or "lingual".

Tooth-root/%	#31 DR	#31 MR	#30 DR	#30 MR	#29
Inferior	42.3%	42.9%	61.8%	54.4%	52%
Buccal	53.8%	51.4%	18%	14.8%	34.7%
Lingual	3.9%	5.7%	20.2%	30.7%	13.3%
	#18 DR	**#18 MR**	**#19 DR**	**#19 MR**	**#20**
Inferior	34%	39%	54.4%	18.2%	58.9%
Buccal	64%	57%	22.2%	50%	31.6%
Lingual	3%	4%	23.3%	31.8%	9.5%

Table 15. Relative position of the mandibular canal to each individual tooth/root

Tooth/%	2nd premolar	1st molar	2nd molar
Buccal	33%	18.3%	57%
Inferior	55.5%	55.2%	40%
Lingual	11.4%	26.5%	2.9%

Table 16. Relative position of the mandibular canal to each tooth

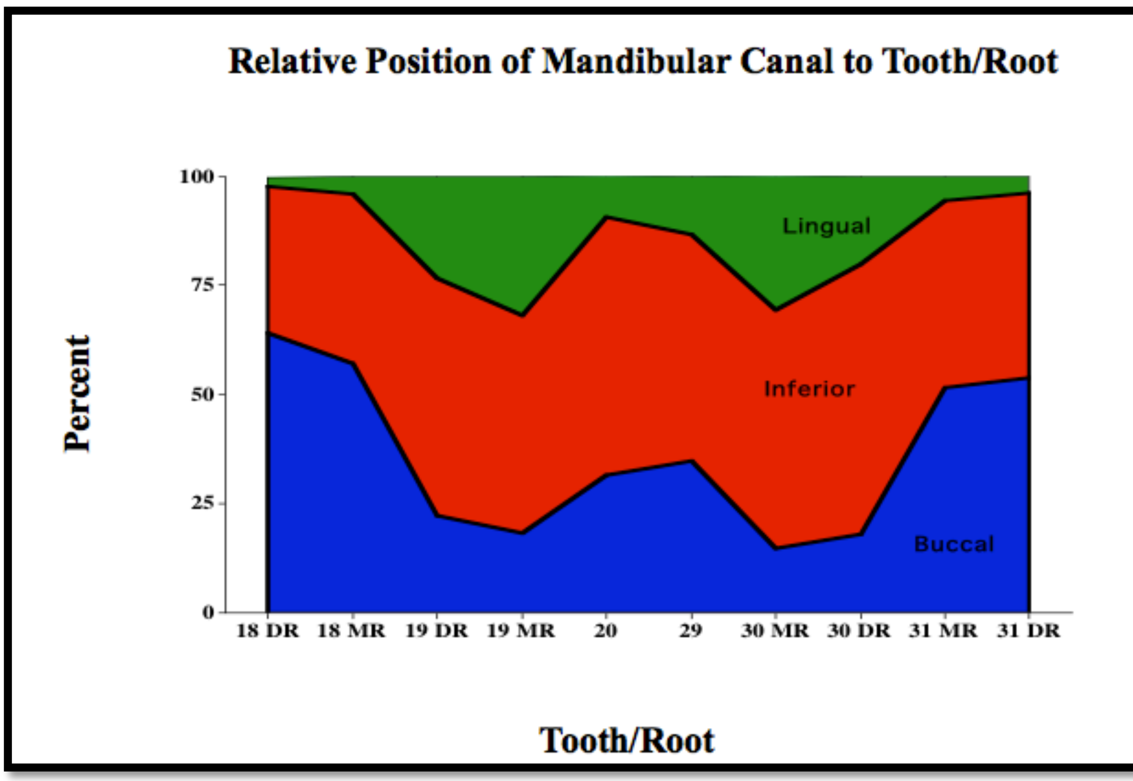

Figure 11. Relative position of the mandibular canal to tooth/root

Sex comparisons (Two group t-tests) for the horizontal distance of the mandibular canal center to each tooth/root are presented in *Table 17*.

Measure	**P-value**
n_hor_ramc_DR18	0.5218
n_hor_ramc_MR18	0.8044
n_hor_ramc_DR19	0.2486
n_hor_ramc_MR19	0.3751
n_hor_ramc20	0.0813
n_hor_ramc21	0.4415
n_hor_ramc28	**0.0068**
n_hor_ramc29	0.1085
n_hor_ramc_DR30	**0.0062**
n_hor_ramc_MR30	**0.0007**
n_hor_ramc_DR31	0.1497
n_hor_ramc_MR31	0.5876

P-values < 0.05 were considered statistically significant. SAS V9.3 (SAS Institute, Inc., Cary, NC) was used for the analyses. None of the p-values are adjusted for multiple comparisons.

Table 17. Sex comparisons (Two group t-tests) for the horizontal distance of the mandibular canal center to each tooth/root

From *Table 17* above, we see a significant difference regarding the relative position of the mandibular canal between males and females for tooth #28, and the mesial and distal root of tooth #30.

DISCUSSION

The purpose of this study was to provide information regarding the anatomic dimensions of the posterior mandibular teeth at the optimal root resection level (3mm form the apex), the diameter of mandibular canal, the buccal and lingual bone thickness in the two previously mentioned locations, as well as the relative position of the canal to the apices of the teeth. Knowledge of these dimensions will aid the clinician performing apical surgery, providing a three-dimensional reconstruction of the area of interest, and also during emergencies where nerve decompression may be required to remove deleterious material previously expressed into the mandibular canal causing nerve impairment (eg dysesthesia; *Figure 1*).

Previous cadaver studies provide some anatomical information, but the often-limited sample size was possibly a confounding factor for the conclusions drawn. As the use of CBCT is evolving in dentistry, information can now be obtained non-invasively and evaluated in sufficient quantity since large numbers of scans are utilized with realistic depiction of the mandibular anatomy, overcoming the sample size limitation often seen with cadaver studies. For the presurgical assessment of the relative position of the mandibular canal to the apices of the teeth, computed tomography has been proven better than periapical and panoramic radiography [68], as it allows for a realistic reconstruction of the area in a true 1:1 anatomic representation. Sato et.al confirmed the anatomical findings of computerized tomography by performing macroscopic dissection, showing that the main trunks of the inferior alveolar artery, vein, and nerve were in close proximity to the apex of the second molar. [69] In a different study by Kim et.al, the I-CAT Classic CBCT was found to measure distances from the apices of the posterior teeth to the mandibular canal as accurately as direct anatomic dissection. [70]

What is advantageous for the clinical relevance and application of the present study is that the CBCT studies of the mandible demonstrate a better image quality than the maxilla, possibly due to the greater contrast between the dental alveolus and the cortex surrounding it. [71] This results in high quality imaging of the areas of interest. The current study found that the mandibular canal has a pretty uniform diameter as it is progressing toward the midline. No statistical difference regarding the mandibular canal diameter was noted between different teeth areas or between genders.

The average buccal bone thickness over the mandibular canal increased significantly from the premolars to the 2nd molars, while the average lingual bone thickness increased from the molar to the premolar area. These findings confirm an almost uniform total thickness of buccal and lingual cortical bone surrounding the mandibular canal.

The horizontal position of the mandibular canal in relation to the apices of the mandibular posterior teeth was found to be mostly on the buccal of the 2nd molar (57%), with the next bigger prevalence being inferiorly to the apices of the 2nd molar (40%). As the inferior alveolar nerve is progressing toward the midline, the canal was found directly below the apices of the first molar 55.2% of the time, with the next trend being towards the lingual 26.5% of the time. For the second premolar area, the mandibular canal was found below the apex of the tooth 55.5%, buccally 33% and lingually 11.4%. Overall, the mandibular canal was inferior to the apices of the posterior teeth 38-58% of the time. The mandibular canal was seen buccal of the tooth apex >50% of the time near the 2^{nd} molar, and lingual to the tooth apex near the mesial root of the 1^{st} molar (26%). Denio et.al found that in a typical S-shaped configuration of the mandibular canal, the canal was located buccal to the distal root of the second molar, crossed to the lingual below the second molar mesial root, continued lingual to the first molar, and crossed back to the buccal to the apex of the second premolar. [19] The current study is in agreement with the Denio study, as the position of the mandibular canal is inferior to the root apex most often in the area of the mandibular second premolar and second molar. The relative closeness of the nerve to the tooth apex was previously examined by Kovisto et al, using CBCT scans, and the 2^{nd} molars were most closely approximated to the mandibular canal. [21]

The average distance from the outer buccal cortex to the apex of the tooth at the optimal resection level averaged 2.08mm for the first premolar, 2.19mm for the second premolar, 2.30mm and 3mm for the first molar mesial (MR) and distal (DR) root, and 5.16mm and 6.35mm for the second molar mesial (MR) and distal (DR) root, respectively. In other words, the more posterior the tooth is located in the mandible, the greater the amount of buccal bone that needs to be removed while performing the buccal osteotomy.

From the present study, it can also be noted that the buccal bone over the mandibular 2^{nd} molars was more than twice the thickness of that over the 1^{st} molars, providing a reason for limiting apical surgery to tooth roots anterior to mandibular 2^{nd} molars. This finding applied to both male and female subjects.

The thickness of the lingual bone was almost consistent for the first premolar, second premolar and the mesial and distal roots of the first molar, averaging 4.21mm, 4.50mm, 4.33mm and 4.15mm, respectively. The distance from the tooth apex to the outer lingual cortex was significantly less for the mesial and distal root of the second molar, with an average of 2.80mm and 2.42mm, respectively. Since the clinician most commonly performs the osteotomy from a buccal approach, the clinical relevance of these measurements is of great importance when it comes to extrusion of materials or endodontic instruments through the mesiolingual canal of the molars; such iatrogenic errors can potentially be corrected through a buccal approach, but the integrity of the lingual cortical plate and its limited thickness over the apex of some teeth must be considered for the design of the surgical intervention. Even in cases of periradicular curettage and granulomatous tissue removal from the second molar area, the integrity of the lingual cortical plate can be compromised, and possibly result in lingual soft tissues trauma.

After performing the buccal osteotomy, the average root thickness to a complete through and through root resection is the other parameter that should be considered, in order to determine if a surgical approach can be the treatment of choice. As we move away from the midline, the average root thickness increases. The latter, in combination with the increasing buccal bone thickness and the progressively limited visibility, is making the root end resection challenging even for the experienced endodontist. The average root thickness at the resection level was found to be 4.30mm for the first premolar, 4.39mm for the second premolar, 5.77mm and 5.28mm for the mesial and distal root of the first molar, 5.42mm and 4.58mm for the mesial and distal root of the second molar, respectively.

The significantly bulkier mesial roots of the first and second molar, in combination with the greater thickness of buccal bone covering the roots, can be limiting factors for surgical intervention at the area of the mandibular molars. The total distance (buccal cortex to root + root thickness) to a complete resection will average about 6.38mm for the first premolar, 6.58mm for the second premolar, 8.07mm and 8.28mm for the mesial and distal root of the first molar, and 10.58mm and 10.93mm for the mesial and distal root of the second molar, respectively. As a result, the distance that needs to be "covered" to a complete root end resection for the second molar (almost 11mm) is about double the distance for the premolar teeth resection, and this makes the apical surgery extremely difficult for the second molar.

The mandibular thickness at the resection level was calculated by adding the average buccal and lingual bone thickness over the root to the average root thickness. Likewise, the mandibular thickness at the mandibular canal level was calculated by adding the average buccal and lingual bone thickness over the canal to the average mandibular canal diameter. The mandibular thickness was found to be greater for male subjects when compared to female subjects, and this applied to both the mandibular canal level and the 3mm from the tooth apex level.

With the major technologic advancements of 3-D imaging, the use of ultrasonics, and the application of the dental operating microscope in the field of the dentistry, the clinician is now able to more accurately complete the presurgical assessment, plan and modify the flap and osteotomy design and extension with respect to the adjacent anatomical structures, and perform the apical surgery with greater efficiency, minimizing the risks for the patient. Limiting factors for the conventional radiographic techniques are distortion and magnification of the anatomic structures, which can range from 3.4% for periapical radiographs to more than 14% for panoramic radiographs. [72] Furthermore, the application of CBCT is overcoming the other major drawback of the two dimensional radiographic exams, which is the lack of information in the buccolingual plane. [73]

The inferior alveolar/mental nerve location is a critical factor when planning any surgical intervention on the posterior mandibular area. The success rate of root-end surgery has been recently reported to be $\geq$ 90% [18,74,75], and it can provide a viable option to functionally retain teeth that otherwise would be condemned to extraction. Therefore, it is imperative for the endodontist performing the apical surgery to evaluate the anatomy of the inferior alveolar/mental nerve and its relative position to the roots of mandibular posterior teeth preoperatively. The use of cone beam computed tomography will provide a realistic 3-D reconstruction of the anatomical structures and teeth, when compared to periapical and panoramic radiography.

A classic study by Goldman et.al demonstrated that when interpreting conventional periapical radiographs for success and failure criteria, presence or absence of rarefaction, examiners agreed only 47% to 73% of the time. [76] Interestingly, even when the same examiner evaluated the same conventional periapical image 6 months later, they agreed with themselves 75 to 83% of the time. [77] These findings were confirmed for digital periapical radiography by Tewary et.al, who noted that the interpretation of a dental radiograph (conventional or digital) is subjective, and the factors that appeared to have the most impact were the examiner's experience and familiarity with a given digital system. [78] As a result, a limitation of the present study is that although all the examiners where calibrated in order to perform the evaluations and measurements uniformly, only one evaluator examined each scan once.

In order to verify that the data collected provides correct information for the parameters evaluated, the same observer or another observer would need to reevaluate the scans, in order to increase the intra- and inter-observer reliability.

CONCLUSION

Overall, knowledge of the mandibular posterior tooth/root thickness for apical resection, its relative position to the mandibular canal, as well as the buccal and lingual cortical bone thickness over the root and the mandibular canal, is beneficial to the endodontist and can provide a knowledge base. Application of CBCT imaging can aid the surgeon performing the RER/REF. In contrast to the Simonton et.al study, which evaluated only the mesial and distal roots of mandibular molars [24], this study is the first to provide average tooth and bone thickness measurements for the resection and the mandibular canal level, categorized by each individual tooth/root type.

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APPENDIX

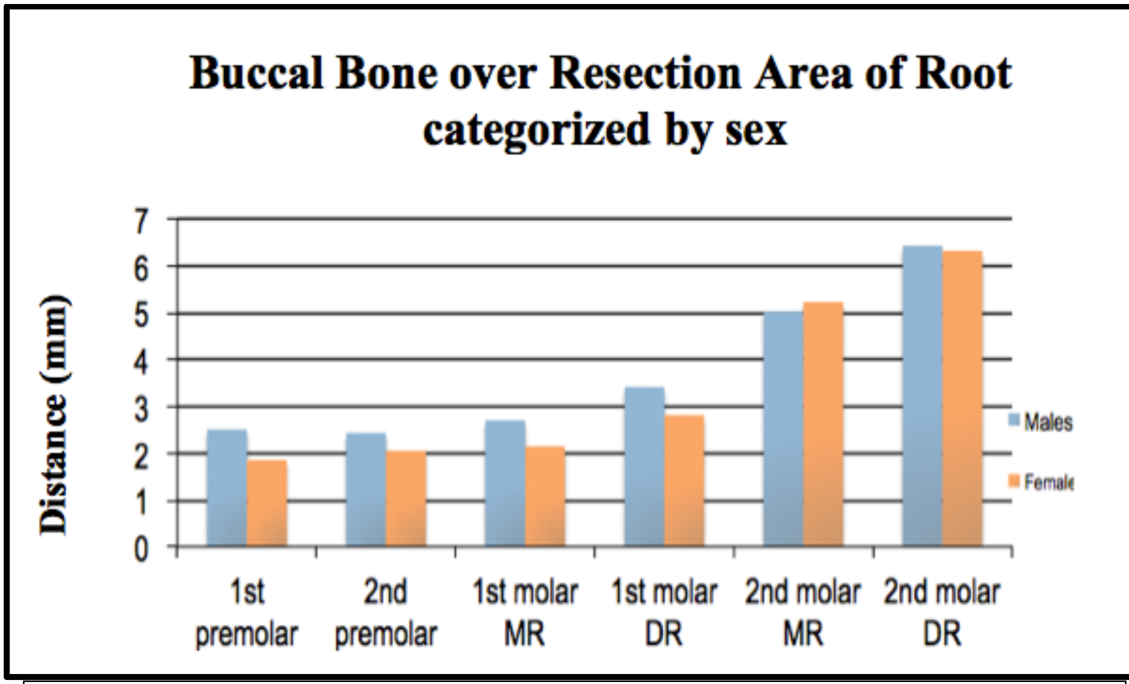

Figure 12. Buccal bone thickness over the resection level (3mm from the apex) categorized by sex

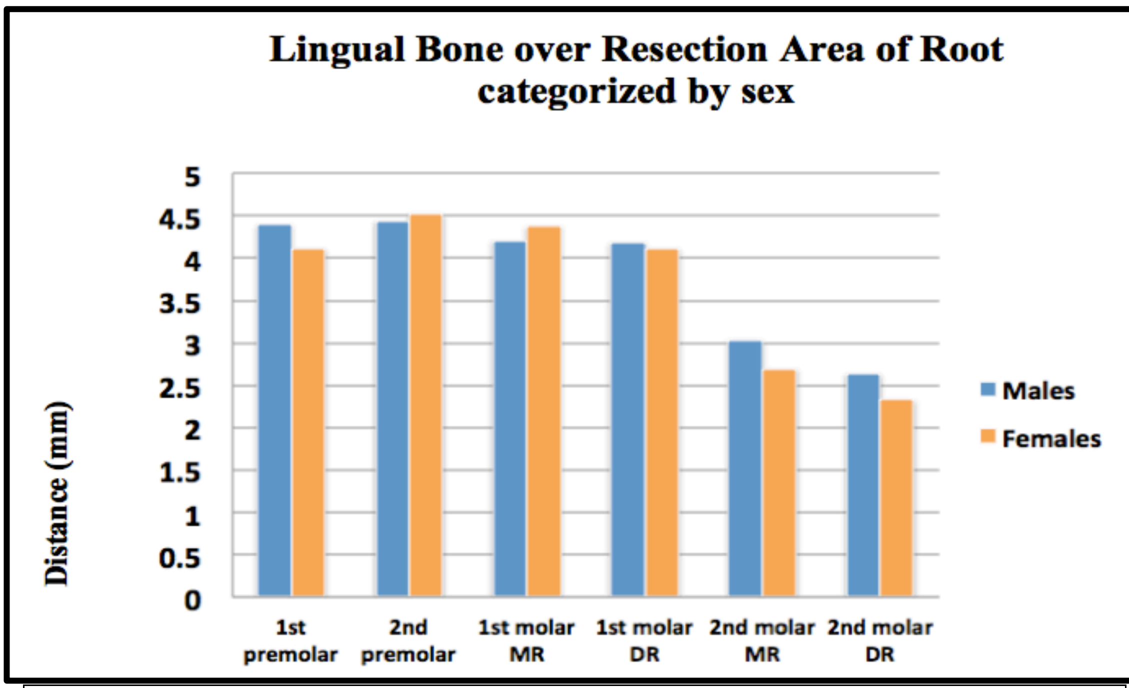

Figure 13. Lingual bone thickness over the resection level (3mm from the apex) categorized by sex

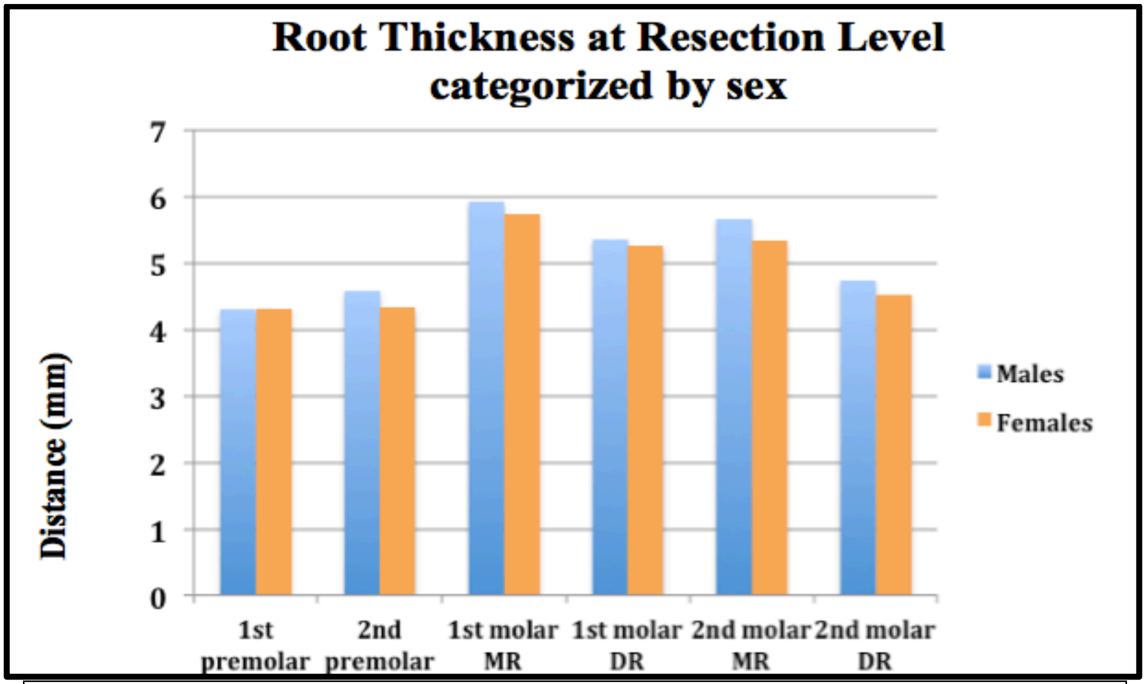

Figure 14. Root thickness over the resection level (3mm from the apex) categorized by sex

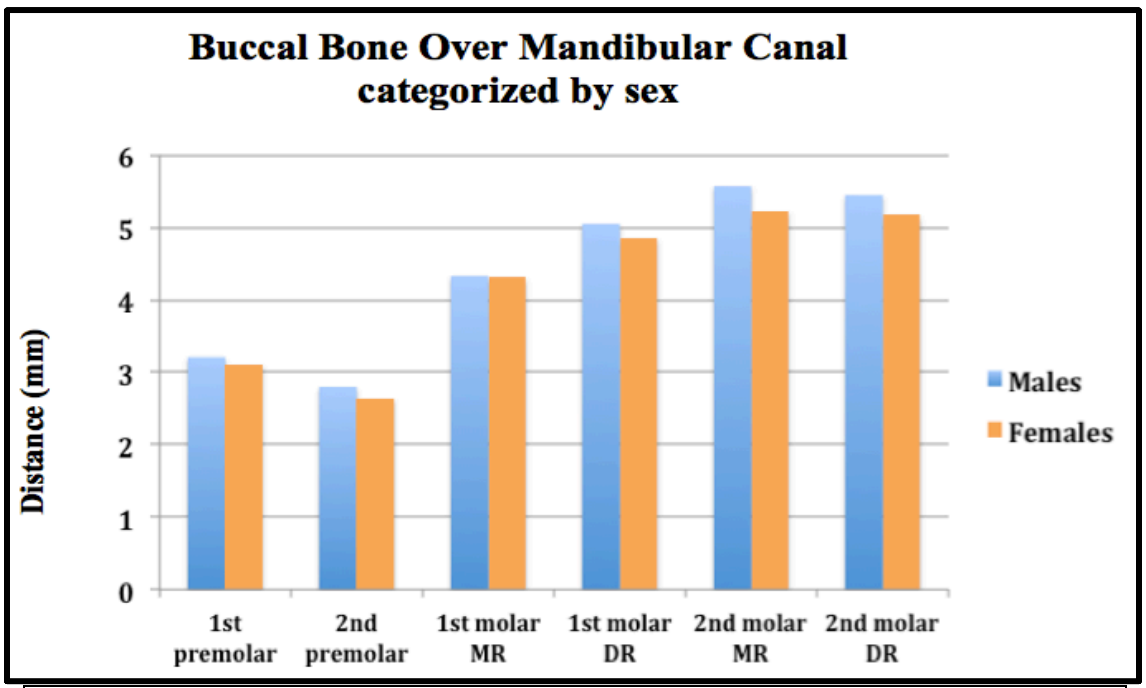

Figure 15. Buccal bone thickness over the mandibular canal categorized by sex

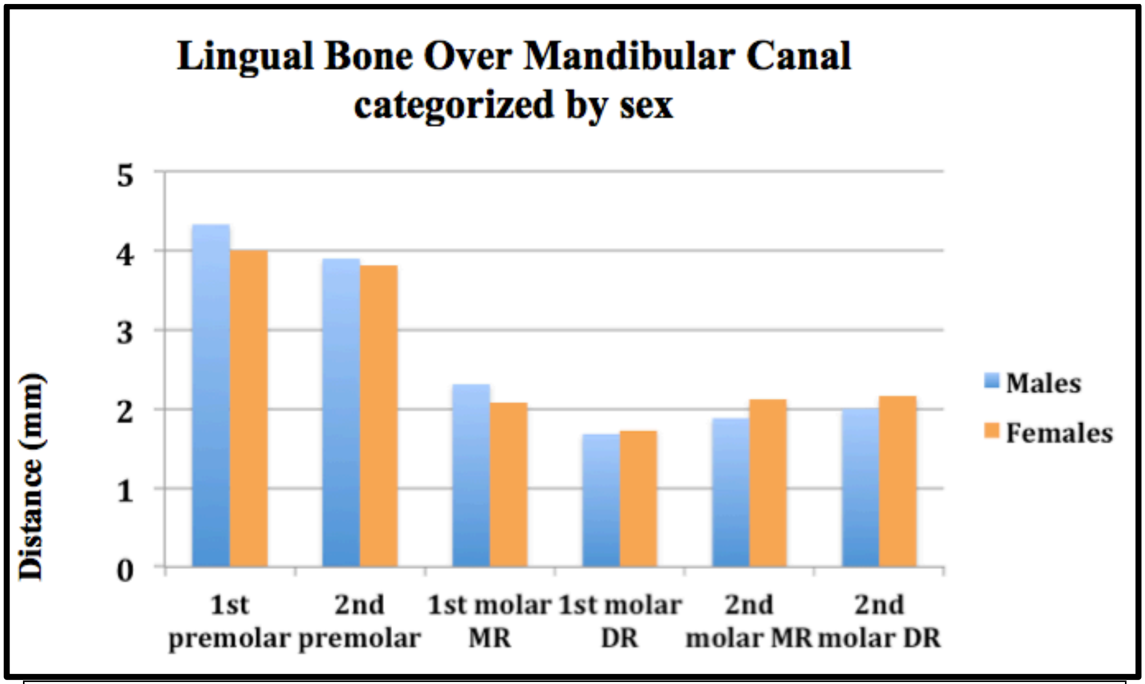

Figure 16. Lingual bone thickness over the mandibular canal categorized by sex

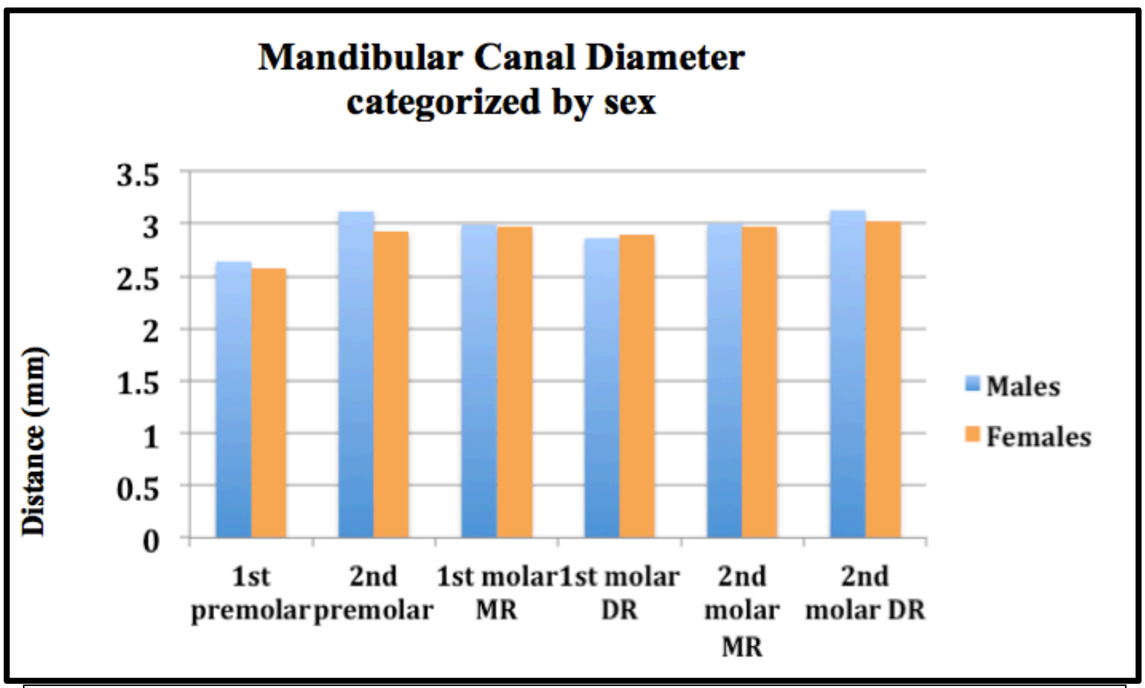

Figure 17. Mandibular canal diameter categorized by sex

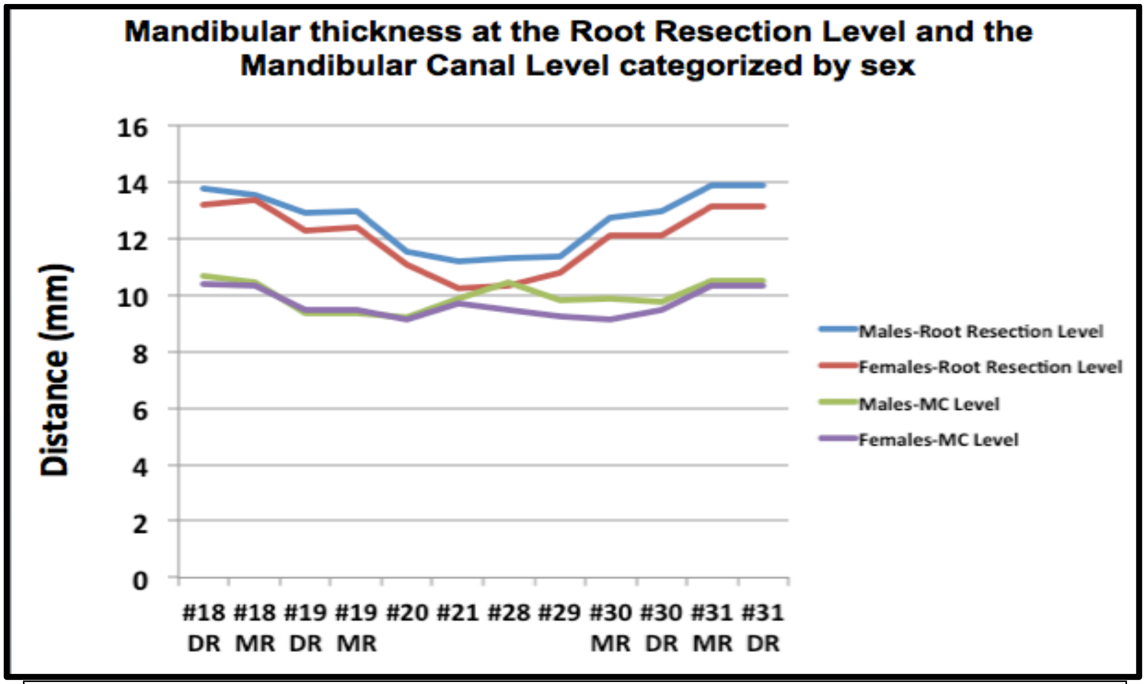

Figure 18. Mandibular thickness categorized by sex