MICRO-COMPUTED TOMOGRAPHY CHARACTERISATION OF THE ROOT AND CANAL MORPHOLOGY OF MANDIBULAR FIRST PREMOLARS WITH DEEP RADICULAR GROOVES

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by

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ASUDAS	Arizona State University dental anthropology scoring system
AAE	American Association of Endodontists
CBCT	Cone Beam Computed Tomography
CCD	Charged Coupled Device
CEJ	Cementoenamel Junction
CLT	Clearing Technique
CT	Computed Tomography
DOM	Dental Operating Microscope
DPR	Digital Periapical Radiography
FDI	Federation Dentaire Internationale
FOV	Field of View
JEPeM	Jawatankuasa Etika Penyelidikan Manusia
LP	Lower Premolars
LFP	Lower First Premolars
MD	Mesio Distal
MFP	Mandibular First Premolar
Micro-CT	Micro Computed Tomography
NaOCl	Sodium Hypochlorite
0-C-F	Orifice-Canal-Foramen
OCT	Optical Coherence Tomography
PPT	PowerPoint
RCC	Root Canal Configuration
RG	Radicular Groove

SD	Standard Deviation
2D	Two Dimensional
3D	Three Dimensional

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PENCIRIAN TOMOGRAFI BERKOMPUTER MIKRO UNTUK MORFOLOGI AKAR DAN SALURAN PREMOLAR PERTAMA MANDIBULAR DENGAN ALUR RADIKULAR YANG DALAM

ABSTRAK

Pengetahuan yang mencukupi mengenai saluran akar gigi serta kerumitan dan variasinya adalah penting dalam menjayakan rawatan saluran akar. Kajian ini bertujuan untuk mencirikan morfologi akar dan saluran akar gigi premolar pertama mandibular yang mempunyai alur radikular dalam kalangan populasi Malaysia dengan menggunakan mikro-CT, menggunakan sistem klasifikasi baru-baru ini diperkenalkan, serta menggambarkan morfologi saluran akar secara langsung, dengan menggunakan mikroskop dan radiografi, dan menentukan aplikasi sistem klasifikasi baru-baru ini diperkenalkan dalam pendidikan melalui kajian selidik. Kajian ini melibatkan tiga komponen yang berlainan: 1) Analisis mikro-CT terhadap 133 premolar pertama mandibular dengan alur radikular yang dalam dalam kalangan subpopulasi Malaysia, menilai ciri-ciri alur radikular, konfigurasi saluran akar, saluran aksesori, kelaziman kehadiran ismus, dan ketebalan dentin; 2) Penilaian sampel yang sama menggunakan penglihatan langsung, pemeriksaan mikroskopi serta radiografi untuk membandingkan kaedah penilaian klinikal dengan hasil penemuan mikro-CT; 3) Kajian selidik terhadap 1082 pelajar pergigian di kolej pergigian-kolej pergigian negara India untuk menilai persepsi mereka terhadap penggunaan sistem klasifikasi baru-baru ini diperkenalkan. Hasil kajian menunjukkan bahawa alur radikular kebanyakannya terdapat di bahagian distal (59.1%) dan bahagian mesial (39.8%). Ukuran purata untuk alur radikular adalah: Jarak dari CEJ ke bahagian koronal alur radikular Purata ± SD (4.92±1.18 mm), jarak dari bahagian apikal alur radikular ke apex akar gigi (2.35 ± 1.56), dan panjang alur radikular (6.69 ± 1.42). Kedalaman purata alur radikular adalah 1.48 ± 0.54 mm, dengan variasi pada aras rujukan yang berbeza. Ketebalan dentin pada alur radikular merupakan 0.69±0.26 mm berdasarkan ukuran dalaman dan 1.15±0.30 mm berdasarkan ukuran luaran, dengan variasi pada aras rujukan yang berbeza. Pelbagai konfigurasi saluran akar diperhatikan. Konfigurasi $^{1}MFP^{1-2}$ didapati paling umum, membentuk kelaziman 19.54% daripada

kes-kes yang diperhatikan. Variasi morfologi saluran aksesori adalah pelbagai, dengan ketiadaan saluran aksesori (18.0%) dan kehadiran delta (21.8%) sebagai kelaziman. Saluran aksesori kebanyakannya hadir di bahagian terakhir (52.29%) dan kedua-dua bahagian tengah dan terakhir (28.44%) akar gigi. Menurut klasifikasi Fan *et al.* (2010), ismus Jenis 2, 3, dan 4 diperhatikan dengan kekerapan yang berbeza. Kaedah penilaian secara klinikal menunjukkan perbezaan yang signifikan dalam konfigurasi saluran akar yang diperhatikan berbanding dengan imej mikro-CT (p<0.001). Pengedaran dan peratusan radiografi dengan perbandingan mikro-CT untuk pemeriksa 1 dan 2 mengungkapkan perbezaan signifikan antara konfigurasi saluran akar (p <0.001). Persepsi para pelajar pergigian terhadap sistem klasifikasi baru-baru ini diperkenalkan di kolej pergigian-kolej pergigian negara India dikaji untuk menilai kebolehgunaan dan penerimaannya. Secara keseluruhan, 92.88% dan 91.78% peserta kajian mendedahkan bahawa sistem klasifikasi Ahmed *et al.* (2017) untuk adalah lebih praktikal dan tepat berbanding dengan sistem klasifikasi Vertucci dan konfigurasi tambahannya yang lain. Perbezaan yang signifikan dilaporkan dalam kalangan jawapan pelajar-pelajar dari segi kebolehgunaan (P <0.001) dan ketepatan (P <0.001). Dengan konfigurasi yang paling kerap, iaitu $^{1}MPM^{1-2}$. Jenis istmus yang paling kerap ditemui adalah Jenis 2. Pelbagai teknik visualisasi, termasuk penglihatan secara langsung, mikroskopi, dan perbandingan radiografi, menyumbang kepada pemahaman yang lebih menyeluruh tentang kelebihan dan kelemahan setiap kaedah. Ini dapat memberi bimbingan kepada para doktor klinikal dalam pemilihan kaedah imbasan yang paling sesuai untuk kes-kes tertentu. Berbanding dengan sistem klasifikasi Vertucci dan konfigurasi tambahannya, para pelajar pergigian pra-ijazah, pasca-ijazah serta pelatih ~~intern~~ di negara India bersetuju bahawa sistem klasifikasi Ahmed *et al.* (2017) adalah lebih praktikal dan tepat untuk mengklasifikasikan morfologi akar dan salurannya.

MICRO-COMPUTED TOMOGRAPHY CHARACTERISATION OF THE ROOT AND CANAL MORPHOLOGY OF MANDIBULAR FIRST PREMOLARS WITH DEEP RADICULAR GROOVES

ABSTRACT

Sufficient knowledge of root canals and their complexity and variations is essential in achieving a successful root canal treatment. This study aimed to characterise the root and canal morphology of mandibular first premolars with radicular grooves using micro-CT in the Malaysian population using a recently introduced classification system, and visualisation of root canal morphology using direct, microscope and radiography and determine the application of recently introduced classification system in education though a survey. The study included three distinct components: 1) Micro-CT analysis of 133 mandibular first premolars with deep radicular grooves in the Malaysian subpopulation, assessing deep radicular groove characteristics, root canal configurations, accessory canals, isthmus prevalence, and dentinal thickness; 2) Evaluation of the same samples using direct vision, microscopy, and radiography to compare clinical assessment methods with micro-CT findings; 3) A survey study undertaken involving 1082 dental students in Indian dental colleges to gauge their perceptions of applying a recently introduced classification system. Results showed that radicular grooves were predominantly located in the distal aspect (59.1%) and mesial aspect (39.8%). The average measurements for radicular grooves were: CEJ-to-coronal groove distance mean ± SD (4.92± 1.18 mm), apical groove to root apex distance (2.35 ± 1.56 mm), and groove length (6.69 ± 1.42 mm). Average depth of the radicular groove was 1.48 ± 0.54 mm, with variations at different reference levels. Dentinal thickness at the radicular groove was measured at 0.69±0.26 mm internally and 1.15±0.30 mm externally, with variations at different reference levels. Multiple root canal configurations were observed, with the $^{1}\text{MFP}^{1-2}$ configuration found to be the most common, comprising a frequency of 19.54% of the observed cases. Accessory canal morphology variations were diverse, with no accessory canal (18.0%) and a delta ($^{1}\text{MFP}^{(D)}$) (21.8%) being prevalent. Accessory canals were most located in the apical third (52.29%) and both

middle and apical thirds (28.44%). According to Fan *et al.* (2010) classification, types 2, 3, and 4 isthmuses were observed in varying frequencies. Clinical assessment methods showed significant differences in observed root canal configurations compared to micro-CT imaging (P<0.001). Distribution and percentage of radiograph with micro-CT comparison for examiners 1 and 2 revealed significant differences between the root canal configurations (P<0.001). Dental students' perceptions of the recently introduced classification system in Indian dental colleges were surveyed to assess its practicality and acceptance. Overall, 92.88% and 91.78% of study participants revealed that the Ahmed *et al.* (2017) classification system to classify the root and canal morphology was much more practical and accurate than that of the Vertucci's classification system and its additional configurations. In conclusion, the current study showed significant variations in the location of the radicular grooves predominantly situated in the distal aspect with the most common root canal configuration being $^{1}MFP^{1-2}$. The most common type of isthmus observed was Type 2. The multiple visualization techniques, including direct vision, microscopy, and radiography comparisons contributed to a more comprehensive understanding of the advantages and limitations of each method, which guide clinicians in choosing the most suitable imaging method for specific cases. In comparison to Vertucci's classification system and supplementary types, the undergraduate and postgraduate dental students, and interns in India agreed that Ahmed *et al.* (2017) classification system is more practical and accurate for classifying the root and canal morphology.

CHAPTER 1

INTRODUCTION

1.1 Background

To ensure successful root canal treatments and to prevent treatment failure caused by misdiagnosis, it is imperative to possess a comprehensive knowledge of root canals and their multifaceted variations (Ahmed *et al.*, 2020a; Buchanan *et al.*, 2020). The root system of the mandibular first premolar is usually single rooted. However, there were numerous reports in the literature of variations with more than one root (Nouroloyouni *et al.*, 2021; Sierra-Cristancho *et al.*, 2021a; Zhang *et al.*, 2020). In specific individuals, a radicular groove (RG) forms on the mesial aspect of the tooth, forming a "C" structure in root cross-sections (Boschetti *et al.*, 2017a). It was presumed that this root distortion occurred because of one interradicular process induced unilaterally when the tooth was developing (Gu *et al.*, 2013b). RGs are invaginations that form during tooth development; formerly, they were linked to the transition from a single root to many roots in mandibular first premolars. Additionally, Tomes' root characteristic, first described by Charles Tomes, refers to the anthropological phenomenon of partially or divided roots of the mandibular first premolars (Büyükbayram *et al.*, 2019).

In dentistry, mandibular premolars that have RG have an essential therapeutic significance. Radicular grooves in mandibular premolar teeth have been linked to anatomical root canal system complexity, including C-shaped canal structure and canal bifurcation (Boschetti *et al.*, 2017a; Lu *et al.*, 2006). These complexities are usually disregarded, and the inability to identify and appropriately treat all root canal systems contributes to the high failure percentage for nonsurgical canal treatment of this group of teeth (11.45%) (Kararia *et al.*, 2012).

The research conducted by Lu *et al.* (2006) revealed that the external root surface of all complex morphology premolars featured a groove or concavity, most commonly located in the middle root's proximal lingual area. When evaluating the canal morphology of mandibular first premolars in a Chinese population, they found that 18% of the teeth had complex root canal morphology when seen on CBCT. Using the same approach, Sikri and Sikri (1994) found that 10.7% of the Indian population had canals with a C-shape. In a population sample from the United States, Baisden *et al.* (1992) examined 106 cross-sections of mandibular first premolars using a stereomicroscope and discovered that complex canal morphology was present in 14% of the teeth. The high rate of endodontic failure on this tooth may be attributable to the complex morphology of the tooth, which makes root canal therapy more challenging (Fan *et al.*, 2008).

Previous studies conducted in the mandibular first premolars with RG using micro-CT have reported the prevalence of RG in the proximal aspects of the mandibular first premolars in the 24%, which were commonly associated with the presence of additional canals (Fan *et al.*, 2008). Liu *et al.* (2013) reported the existence of mesial RG in 27.8 % of the mandibular first premolars analysed in the study (Liu *et al.*, 2013a). Similarly, Gu *et al.* (2013) revealed that the increased severity of RG has shown a decrease in the minimum mesial wall thickness, whereas the mesial wall of the C-shaped canal in the mandibular first premolar is the thinnest zone (Gu *et al.*, 2013a). Another study conducted by Boschetti *et al.*(2017) showed the presence of RG in 14% of the mandibular first premolars from the total sample analysed (Boschetti *et al.*, 2017b). A recently conducted study by Sierra-Cristancho *et al.* (2021) in Chile population reported that 39.25% of the mandibular first premolar from the samples analysed in the study had RG (Sierra-Cristancho *et al.*, 2021a).

The permanent human dentition has shown a considerable variation in root canal morphology (Vertucci, 1984). Several authors introduced classifications for root canal configuration and supplements for the Vertucci classification (Sert and Bayirli, 2004; Vertucci *et al.*, 1974; Weine, 1982; Weine *et al.*, 1969). Weine *et al.* (1969) classified root canal morphology within a single root into three types. Later, in the year 1982, the authors added one more type to the classification, i.e. Type IV (Weine, 1982). In the year 1974, Vertucci *et al.* identified further complex root canal systems. They reported eight types of canal configurations according to the pattern of division in the main root canal from leaving the pulp chamber to the apex of the root and described as follows. Type I: A single main canal is present starting from the pulp chamber to the root apex. Type II: Two separate canals leave the pulp chamber but join to form one canal to the apex. Type III: One canal leaves the pulp chamber, divides into two within the root, and then merges to exit in one canal. Type IV: Two separate and distinct canals are present from the pulp chamber to the apex. Type V: Single canal leaving the pulp chamber but dividing into two separate canals with two separate apical foramina. Type VI: Two separate canals, joins at the middle of the root to form one and extends till apex, just short of apex again divides into two. Type VII: Canal starts as a single until middle third of the root then divide into two separate canals and then rejoins after some distance and then near the apex divides into two again. Type VIII: The pulp chamber near the coronal portion divides into three separate canals extending till the apex (Vertucci *et al.*, 1974).

Sert and Bayirli (2004) added supplementary configurations to Vertucci's classification system. The authors evaluated the root canal configuration in 2800 maxillary and mandibular permanent teeth amongst the Turkish population using the clearing technique. They added fourteen types to Vertucci's classification and numbered them from Type IX to Type XXIII (Sert and Bayirli, 2004). In addition, a new classification was introduced by Ahmed *et al.* (2017). This new system comprises codes for tooth number, the number of roots and types of root canal morphologies. Recently, the authors explained the application and advantages of this new classification of root canal morphology in routine clinical practice and research. Commonly used classification systems given by Weine *et al.* (1969) and Vertucci *et al.* (1974) helped classify many but not all canal morphologies (Ahmed *et al.*, 2017; Ahmed and Dummer, 2018). Several studies found root canal configuration to be highly complex and found non-classifiable canal configurations during the evaluation of internal and external anatomical canal variation using 3D imaging techniques (Kim *et al.*, 2013b; Lee *et al.*, 2014; Leoni *et al.*, 2014; Verma and Love, 2011). Moreover, a study conducted by Filpo-Perez *et al.* (2015) found that about 13% of the samples did not fit Vertucci's classification and its supplemental configurations (Filpo-Perez *et al.*, 2015). Furthermore, a recent study showed 2.2% non-classifiable variables

(Karobari *et al.*, 2020). In addition, the Vertucci classification does not consider the number of roots in the anterior and premolar teeth (Ahmed and Dummer, 2018).

Literature has shown the variation in root and canal morphology of permanent premolars in various populations (Abella *et al.*, 2015; Buchanan *et al.*, 2020; Saber *et al.*, 2019; Tian *et al.*, 2012). Conventional techniques used for the evaluation of root and canal morphology of permanent premolars, which includes clearing and staining (Neelakantan *et al.*, 2011; Vertucci and Gegauff, 1979), polyester casting resin stained with a red pigment was used to make plastic casts of the root canals(Carns and Skidmore, 1973), examination using magnification (Kartal *et al.*, 1998; Neelakantan *et al.*, 2011), cone-beam computed tomography (CBCT) (Abella *et al.*, 2015; Buchanan *et al.*, 2020; Saber *et al.*, 2019; Tian *et al.*, 2012), and micro-computed tomography (micro-CT) (Liu *et al.*, 2013a; Wolf *et al.*, 2020a; Wolf *et al.*, 2020b). Earlier conventional techniques are invasive and need special preparations compared to radiographic procedures.

Several approaches have been documented over the past 30 years for examining the inner and outer structures of human teeth. These include 1) radiography techniques, 2) clearing techniques, 3) transparent tooth modelling techniques, and 4) the histological sections (Kato *et al.*, 2016). Most of these techniques are intrusive, and they analyse the object in only two dimensions, so their findings do not provide an accurate picture of the object's full shape. Micro-computed tomography (micro-CT) has recently been employed for root and canal characterization because of its excellent resolution and lack of specimen degradation. In their investigation using micro-CT, Fan *et al.* (2004) and Gao *et al.* (2006) demonstrated that some isthmuses could be discovered relatively close to the groove, indicating the presence of a risk zone. Furthermore, micro-CT non-destructive scanning has been used to describe and clarify morphological changes in the root canal morphology before and after instrumentation.

Nielsen *et al.* (1995) were the first to recognise and describe the use of micro-CT in the field of endodontic research, and further development was identified with decreased voxel size, which resulted in good-quality of images (Dowker *et al.*, 1997; Rhodes *et al.*, 1999). Micro-CT is non-invasive, preserves tooth structure, enhances the image and is the most suitable technique for root canal morphology compared with other conventional methods and conventional radiographic techniques (Lee *et al.*, 2014; Plotino *et al.*, 2006; Rhodes *et al.*, 1999).

Micro-CT can produce ultra-high resolutions of 1–100 μm *in vitro* using high-resolution detectors and microfocal spot X-ray sources, which is incompatible with the living organism (Kamburoglu *et al.*, 2008; Swain and Xue, 2009). It operates by converging multiple X-rays onto the sample, which are then transformed into a digital image through a sensor (Marciano *et al.*, 2012). Micro-CT has advantages when compared with confocal laser microscopy, scanning electron microscopy, and stereomicroscope, which are used to analyse superficially and cannot produce 3D images and hence require the sectioning of the sample (Nielsen *et al.*, 1995). This quality of micro-CT helps in the quantitative evaluation of volume pre and post-instrumentation, removal of material from root canal or quality of root canal obturation without destruction of the sample and use of the same sample multiple times (Jung *et* *al.*, 2005). The endodontic uses of micro-CT are the evaluation of the internal anatomy, the assessment of the quality of root canal fillings and retreatment, the analysis of the instrumentation of the root canals and the biological and physical properties of the root canal materials (Marciano *et al.*, 2012). The micro-CT is unsuitable for clinical use due to ultrahigh radiation. Additionally, it has a higher cost and longer imaging time for scanning and reconstruction (Ghavami-Lahiji *et al.*, 2021).

Access cavity preparation is an essential and initial step in root canal preparation. Sufficient access to the root system is an essential requirement to effectively carry out the biomechanical preparation of a root canal (Chan *et al.*, 2022; Kapetanaki *et al.*, 2021). Hence, a good access design and approach will provide a piece of information about root canal morphology and its variation under direct vision with or without the microscope, which helps to improve the cleaning and shaping, followed by obturation of the root canals, leading to successful treatment and good prognosis of the treatment (Habib *et al.*, 2017). Access cavity preparation is defined as "the opening prepared in a tooth to gain entrance to the root canal system for the purpose of cleaning, shaping, and obturating" (AAE, 2020). One of the aims of access cavity preparation is to get direct straight-line access to the apical foramen, which helps to determine the root canal morphology and its variation. Furthermore, it can be compared with radiographic evaluation to overcome errors such as missed canals during root canal treatment (Adams and Tomson, 2014). Access cavity preparation is one of the most challenging and complex aspects of endodontic treatment; however, it is one of the keys to endodontic success (Patel and Rhodes, 2007).

One of the significant responsibilities of academics is to deliver the information required to allow dental students to learn and acquire knowledge for clinical practice (Qualtrough, 2014). Inadequate understanding and inability to systematically address usual and unusual anatomical variations of roots and root canals in a given tooth are the leading causes of failure of primary root canal treatments as a consequence of persistent infection within the root canal space that leads to inflammation of the periapical tissues and post-operative pain (Cantatore *et al.*, 2006). Such treatment failures usually result in tooth extraction or require a more invasive and expensive conventional root canal and surgical retreatment procedures with varying clinical success rates depending on several aetiological and technical factors (Ng *et al.*, 2008). The root and canal morphology are essential factors in the endodontic syllabus. The initial educational stage is to properly understand the root and canal morphology before starting the clinical practice of root canal treatment. Classification plays an essential role in this discipline, as it is an excellent tool for precisely describing a subject's morphological or characteristic features(Stains and Talanquer, 2008). Hence, it is essential to examine the ability of students to understand, practice and apply the root and canal morphology classification (Ahmed *et al.*, 2020a).

Survey studies are valid research tools that provide information on respondents' opinions, attitudes and behaviours (Lydeard, 1991). Surveys should be designed well to address research questions appropriately, thus providing an accurate assessment of a given subject. Student questionnaires enable continued assessment, evaluation and improvement of endodontic education programmes and applications (Ahmed *et al.*, 2014; Davey *et al.*, 2015; Mala *et al.*, 2009). Several valuable surveys have been published highlighting current trends and education directions related to endodontic teaching (Al Raisi *et al.*, 2019). However, introducing the new classification in clinical practice and education requires careful planning and the introduction of a novel yet simple way of thinking, which introduces new diagnostic tools and a new decision-making algorithm to support the process leading to diagnosis and case definition.

1.2 Problem Statement

The root and canal morphology of mandibular first premolars, particularly those presenting radicular grooves, pose significant challenges in the endodontics. Existing studies have revealed variations in root anatomical features across diverse populations, including Emirati, Brazilian, Chinese, and Swiss-German populations (Alkaabi *et al*., 2017; Boschetti *et al*., 2017b; Chen *et al*., 2015b; Dou *et al*., 2017; Liu *et al*., 2013b; Wolf *et al*., 2020a). The recent study among the Chilean population further emphasized the prevalence of variations in root canal morphology, with 34.95% exhibiting variations, including the presence of radicular grooves in 39.25% of teeth (Sierra-Cristancho *et al*., 2021a).

One major limitation highlighted is the inability of the Vertucci classification to define the number of roots accurately in premolar teeth and the challenge of classifying many root canals (Ahmed *et al*., 2017; Saber *et al*., 2019). The recently introduced classification system proposed by Ahmed *et al.* (2017) addresses these deficiencies, but its application and validation in different populations, particularly in the Malaysian context, are yet to be explored.

The Malaysian population represents a unique demographic, and data on the root and canal morphology of permanent mandibular premolars using micro-CT is lacking. Furthermore, there is a dearth of information on how the recently introduced classification system proposed by Ahmed *et al*. (2017) performs in the Malaysian population and whether it can enhance education and clinical practice in dentistry.

Additionally, the problem statement acknowledges the absence of data on failures or challenges associated with these anatomical variations specifically in the Malaysian population. Understanding the clinical implications of these variations is crucial for enhancing diagnostic accuracy, treatment planning, and reducing the risk of failures in endodontic procedures (Mazzi-Chaves *et al.*, 2020; Patel *et al.*, 2019). The proposed study aims to fill these critical knowledge gaps and contribute valuable insights to the understanding and management of root and canal morphology in mandibular first premolars, specifically in the Malaysian context.

1.3 Justification

This study aims to characterise the root and root canal morphology of mandibular premolar teeth using a new coding system introduced recently (Ahmed *et* *al.* 2017) with the aid of micro-CT, which provides a clear view of internal and external tooth structure and root canal morphology compared to conventional radiographs and CBCT. A study conducted at the University of Washington (1955) to evaluate the failure rate in non-surgical root canal treatment in teeth showed an 11.45% failure rate with mandibular first premolar, which was the highest failure rate when compared with other teeth in the study (Hull *et al.*, 2003).

Earlier research conducted amongst the American population has revealed that mandibular premolars have a single canal in 100% of the samples (Mueller, 1933). However, studies conducted using CBCT showed variation in the root canal morphology of mandibular premolars amongst different populations showing different Vertucci types (Type II, III, IV, V and VIII) (Alfawaz *et al.*, 2019; Kazemipoor *et al.*, 2015b; Llena *et al.*, 2014; Ok *et al.*, 2014; Qian *et al.*, 2011; Shetty *et al.*, 2014) in contrast to a study conducted in Kuwait population showed Type II was most common (Alenezi *et al.*, 2020). Furthermore, several micro-CT studies revealed the variation in Emirates, Chinese, and Chilean populations (Alkaabi *et al.*, 2017; Dou *et al.*, 2017a; Liu *et al.*, 2013a; Sierra-Cristancho *et al.*, 2021a). and Malaysian populations (Kamaruzaman and Abdul Hamid, 2018; Pang *et al.*, 2022; Samsudin *et al.*, 2023).

This study will help practitioners to understand the root and canal morphology visible clinically and compare the variations in root canal morphology seen using micro-CT, which further helps to achieve proper cleaning and shaping and avoid endodontic treatment failures because of missed anatomy. Furthermore, this study will provide data that would help academicians and clinicians to know anatomical features to implement further during canal preparations. The recently introduced classification system is straightforward and comprehensive, and non-classifiable root canal morphology using Vertucci classification can be classified. Recently conducted surveys showed the acceptance and the potential to be included in the endodontic curriculum (Ahmed *et al.*, 2020a; Salas *et al.*, 2021b). However, more evidence is needed in other countries; hence, this study will provide evidence and comparison with the Malaysian population.

India has a significant number of dental schools and a large community of dental practitioners. Understanding the root canal morphology variations in the Indian population is crucial for the education of dental students and the continuous professional development of practicing dentists. It contributes to the refinement of endodontic education, aligning it with the specific anatomical characteristics encountered in the local population.

1.4 General Objective

To characterise the root and canal morphology of mandibular first premolars with deep radicular grooves using micro-CT in the Malaysian sub-population using a recently introduced classification system and visualise root canal morphology using direct, microscope and radiography. In addition, this study aims to examine the application of the recently introduced classification system in education though a survey conducted among dental students in Indian dental colleges.

1.4.1 Specific Objectives

1. To determine the location, length, and depth of the grooves of permanent mandibular first premolars with deep radicular grooves in the Malaysian sub-population using micro-CT.

2. To determine the dentine thickness of the grooves of permanent mandibular first premolars with deep radicular grooves in the Malaysian sub-population using micro-CT.

3. To determine the variation in root canal morphology of permanent mandibular first premolars with deep radicular grooves in the Malaysian sub-population with micro-CT using Ahmed *et al*. (2017) classification system.

4. To determine the variation in the morphology, number, and type of accessory canal of permanent mandibular first premolars with deep radicular grooves in the Malaysian sub-population with micro-CT using Ahmed *et al*. (2017) classification system.

5. To determine the variation in the isthmus prevalence of permanent mandibular first premolars with deep radicular grooves in the Malaysian sub-population with micro-CT using Fan *et al.* (2010) classification.

6. To determine root canal morphology using direct, microscopic, and radiographic visualisation of permanent mandibular first premolars with radicular grooves in the Malaysian sub-population.

7. To compare the root canal morphology of permanent mandibular first premolars with radicular grooves in the Malaysian sub-population between direct, microscopic, and radiographic visualisation and micro-CT.

8. To evaluate the undergraduate, intern, and postgraduate dental students' perception of applying the recently introduced classification system in Indian dental colleges using a questionnaire.

1.5 Research Questions

1. Is there a significant variation in the location, length, and depth of the grooves of permanent mandibular first premolars with deep radicular grooves in the Malaysian sub-population using micro-CT?
2. Is there a significant variation in the dentine thickness of the grooves of permanent mandibular first premolars with deep radicular grooves in the Malaysian sub-population using micro-CT?
3. Is there a significant variation in root canal morphology of permanent mandibular first premolars with deep radicular grooves in the Malaysian sub-population with micro-CT using Ahmed *et al*. (2017) classification system?

4. Is there any significant variation in the morphology, number, and type of accessory canal of permanent mandibular first premolars with deep radicular grooves in the Malaysian sub-population with micro-CT using Ahmed *et al*. (2017) classification system?
5. Is there a significant variation in the isthmus prevalence of permanent mandibular first premolars with deep radicular grooves in the Malaysian sub-population with micro-CT using Fan *et al.* (2010) classification.
6. Is there a significant difference in the root canal morphology using direct, microscopic, and radiographic visualisation of permanent mandibular first premolars with deep radicular grooves in the Malaysian sub-population?
7. Is there a significant difference in comparison of the root canal morphology of permanent mandibular first premolars with radicular grooves in the Malaysian sub-population between direct, microscopic, and radiographic visualisation and micro-CT?
8. Is there a significance difference in the undergraduate, intern and post graduate dental students' perception of the application of the recently introduced classification system in Indian dental colleges using a questionnaire?

1.6 Hypothesis

1.6.1 Null Hypothesis

1. There is no significant variation in the location, length, and depth of the grooves of permanent mandibular first premolars with radicular grooves in the Malaysian sub-population using micro-CT.
2. There is no significant variation in the dentine thickness of the grooves of permanent mandibular first premolars with radicular grooves in the Malaysian sub-population using micro-CT.
3. There is no significant variation in root canal morphology of permanent mandibular first premolars with radicular grooves in the Malaysian sub-population with micro-CT using Ahmed *et al*. (2017) classification system.
4. There is no significant variation in the morphology, number, and type of accessory canal of permanent mandibular first premolars with radicular grooves in the Malaysian sub-population with micro-CT using Ahmed *et al*. (2017) classification system.
5. There is no significant variation in the isthmus prevalence of permanent mandibular first premolars with radicular grooves in the Malaysian sub-population with micro-CT using Fan *et al.* (2010) classification.
6. There is no significant difference in the root canal morphology using direct, microscopic, radiographic visualisation of permanent mandibular first premolars with radicular grooves in the Malaysian sub-population.
7. There is no significant difference in comparison of the root canal morphology of permanent mandibular first premolars with radicular grooves in the Malaysian sub-population between direct, microscopic, and radiographic visualisation and micro-CT.
8. There is no significance difference in the undergraduate, intern and post graduate dental students' perception of the application of the recently

introduced classification system in Indian dental colleges using a questionnaire.

CHAPTER 2

LITERATURE REVIEW

2.1 Tooth Anatomy in the Human Dentition

The human dentition, crucial for functions like mastication, speech, and aesthetics, comprises primary (deciduous) and permanent teeth. Primary teeth include incisors for cutting, canines for tearing, and molars for grinding. Permanent teeth, larger and more robust, consist of incisors, canines (cuspids), premolars (bicuspids), and molars, each serving specific functions in chewing and tearing. Tooth anatomy involves distinct regions like the visible crown, the neck connecting crown and root, and the root embedded in the jawbone. Essential tooth tissues include enamel, the outermost protective layer; dentine, forming the bulk beneath enamel; and pulp, housing nerves and blood vessels. Understanding the anatomy of teeth is essential for dental professionals in diagnosis, treatment, and maintaining oral health (Robert, 2023). Different numbering systems like the Universal Numbering System, Palmer Notation System, and FDI System uniquely identify each tooth. In this intricate dental system, mandibular first premolars hold significance, and understanding their root morphology and canal system is crucial for successful endodontic treatments (Morris AL and P, 2023; Rahimi *et al.*, 2007).

2.2 Root Morphology

The study of the external and internal anatomy of different teeth groups using many *in vitro* and in vivo techniques was done at the beginning of the 20^{th} century. Normal root morphology of permanent maxillary and mandibular teeth is single rooted. Few reports have documented the occasion of maxillary teeth with more than one root (Calvert, 2014; Gondim *et al.*, 2009; Lin *et al.*, 2006). Several studies revealed the possibilities of two roots in mandibular first premolars amongst Kuwait, China, and Iran populations (24.9%, 0.6%, and 14.4%), respectively (Alenezi *et al.*, 2020; Dou *et al.*, 2017a; Kazemipoor *et al.*, 2015b).

2.2.1 Root Morphology in Mandibular First Premolars

The mandibular first premolars are usually single rooted, but the root morphology of the mandibular first premolar can be highly complex, and extra root(s) can be found. Scott and Turner described the accessory root of the mandibular first premolar as Tome's root (Scott and Turner, 1997). The literature showed the variation of number roots(0.7 to 15% with 2, 0.2 to 2.4% with 3 and 0.6 % with 4 roots) in mandibular first premolars(Geider *et al.*, 1989; Iyer *et al.*, 2006; Schulze, 1970; Zaatar *et al.*, 1997). Another study conducted by Trope et al. (1986) evaluated the number of roots in mandibular first premolars with the incidence of the patient, revealed 2 roots in (5.5, 10.9, 16.2 %) Caucasian, African American and Caucasian and African American respectively (Trope *et al.*, 1986). Various micro-CT studies showed variation in the root of mandibular first premolars (Dou *et al.*, 2017a; Sierra-Cristancho *et al.*, 2021a).

Roots can bifurcate when Hertwig's Epithelial Root Sheath (HERS) divides to form two similar roots or fold the HERS to form an independent root, which may have various morphological features (Ahmed and Abbott, 2012). It is generally considered that the teeth with bifurcation in the coronal and middle third of the root will have two roots clearly, whereas if the bifurcation is in the apical third, which is near the root apex, it is controversial. The bifurcation at the root apex can be classified using Turner's (1981) classification: (i) a single-rooted tooth with a bifid root apex, where the bifurcation at less than $1/3^{rd}$ to $1/4^{th}$ of the total root length and (ii) a single-rooted tooth with double apex, where bifurcation is not clear but has two distinct root tips(Turner, 1981).

2.2.2 Radicular Grooves

The radicular grooves (RG) are the development depressions in the proximal surface of the root, and it was suggested that the induction of the interradicular process during the root development might be the reason for this root deformation (Shields, 2005). The presence of this may increase the area and load-bearing capacity of the periodontal membrane, and further depth may act as a reservoir for dental plaque and calculus, increasing the difficulty of managing periodontal disease (Simon *et al.*, 2000; Tomes, 1923). Concerning the external morphology, radicular grooves are frequently observed on the mesial or distal surfaces of the root of mandibular first premolars, and they usually exhibit complex anatomical features internally, which includes canal bifurcations, C-shaped canals or isthmus, among other root configurations (Awawdeh and Al-Qudah, 2008; Cleghorn *et al.*, 2008; Fan *et al.*, 2008; Gu *et al.*, 2013a; Gu *et al.*, 2013b; Liu *et al.*, 2013a; Lu *et al.*, 2006; Sierra-Cristancho *et al.*, 2021a).

Using micro-CT, Fan *et al.* (2008) found that the presence of a C-shaped root could lead to significant morphologic differences in the root canal system due to the presence of radicular grooves. Also, the mesial wall of the C-shaped canals in mandibular first premolars was found to be the weakest zone, and the minimum mesial wall thickness decreased with the greater severity of the radicular groove, as was previously noted by Gu *et al.* (2013a). However, there has been a lack of research on the connection between radicular grooves and root canal morphology in mandibular first premolars. Previous studies have mainly focused on the incidence of radicular grooves and their influence on root morphology (Chen *et al.*, 2015a; Fenelon and Parashos, 2022; Gu *et al.*, 2013b).

The Arizona State University Dental Anthropology System (ASUDAS) is a morphological scoring system utilized by anthropologists for gathering data on human dentition. This system focuses on traits that are both reliable and readily observable, making it a valuable tool in the field of dental anthropology (Venkatesh *et al.*, 2019). According to the findings of previous research, mandibular first premolars with multiple and complex canals have a more significant percentage of radicular grooves and a more complex root morphology than mandibular first premolars with single and simple canals (Chen *et al.*, 2015b; Fan *et al.*, 2012; Gu *et al.*, 2013b; Ordinola-Zapata *et al.*, 2013).

Gu *et al.* (2013b) found that the incidence of complicated root canals was 18.7% in shallow grooves (Arizona State University dental anthropology scoring system (ASUDAS = 1), 37.0% in moderately deep grooves (ASUDAS = 2), and 90% in deep grooves (ASUDAS = 3). In the same research, transverse accessory canals were found in the radicular grooves of only 10% of mandibular first premolars. Another study found that the combined prevalence of radicular grooves among ASUDAS grades 3 and 4 was 85.7%, substantially more significant than that among ASUDAS type 1 and 2 (Guerreiro *et al.*, 2019).

2.3 Root Canal System and Morphology in Permanent Dentition

The pulp chamber mainly consists of a single cavity with multiple pulp horns in the coronal part of the tooth. With age, there will be a reduction in the size of the pulp chamber, mainly because of the formation of secondary dentine, which could be physiologic or pathologic. In response to pulpal irritation, tertiary dentine or reparative dentine may be formed, which is uneven in structure. The floor of the pulp chamber exhibits the root canal orifices, which are usually below the cusp tips. Root canals keep tapering as they extend toward the root apex so that the narrowest part will be at the apical foramen 0.5 to 1.0 mm short from the anatomic apex (Figure 2.1).

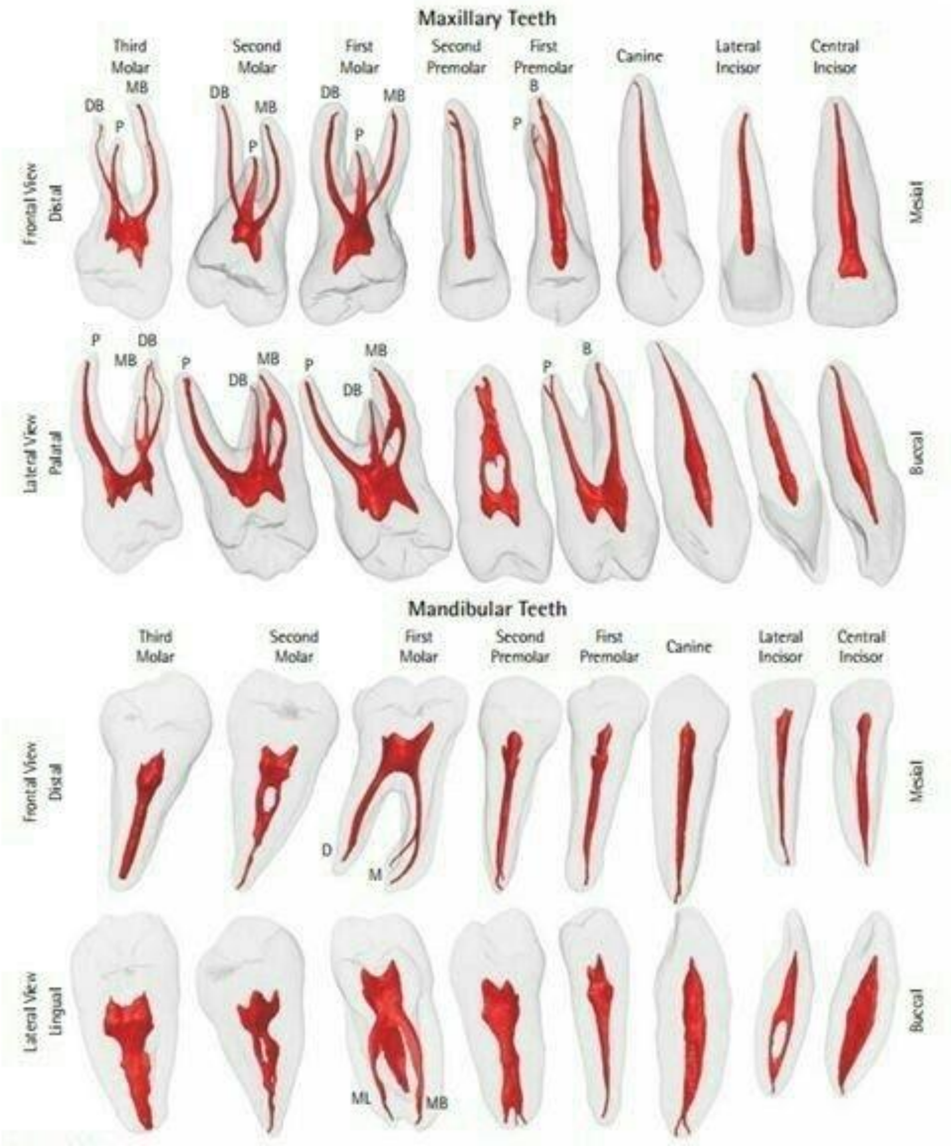

Figure 2.1 Root canal morphology in permanent dentition adapted from (Chandra and Gopikrishna, 2014)

According to the findings of a study conducted on human teeth by Brescia (1961), the most varied canal morphology was found in the mandibular first premolar. Due to changes in root canal morphology and the inaccessibility of additional canals, the mandibular first premolar was shown to have the highest rate of failure in the Washington study (Ingle and Beveridge, 1985). It has been observed that the rates of mandibular first and second premolars with two or more root canals range from 2.7% to 65% and 0-43%, respectively (Baisden *et al.*, 1992; Mueller, 1933; Sert and Bayirli, 2004).

It has been recognized that male and female root canal systems differ slightly (Ahmed *et al.*, 2007; Trope *et al.*, 1986; Vertucci, 1984). The vast majority of investigations into the root canal morphology of mandibular first premolars were carried out on participants from the Iranian (Rahimi *et al.*, 2007), American (Vertucci, 1984), Indian (Velmurugan and Sandhya, 2009), Far Eastern (Walker, 1988), and Turkish (Caliskan *et al.*, 1995) populations, respectively.

2.4 Mandibular First Premolars

The mandibular first premolar is the fourth tooth from the median line and the first posterior tooth in the mandible; they are two in number and situated on the right side of the mandible and the other on the left. They are immediately posterior to the mandibular canines and anterior to the second premolars. Developed from four lobes, three buccal (the middle is well developed to form a buccal cusp) and one lingual