Root and canal morphology of the maxillary first molar: A micro-computed tomography-focused observation of literature with illustrative cases.

Part 2: Internal root morphology

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ABSTRACT

The complexity of root canal morphology can influence cleaning and shaping of the root canal system and, ultimately, treatment outcomes. Undiscovered root canal morphology can greatly reduce the prognosis of endodontic treatment due to the preservation of offending organisms and their by-products. The maxillary first molar has been identified as one of the most challenging teeth to treat endodontically due to its complex internal anatomy, the presence of additional and accessory canals and intricate root canal configurations. This paper is the second of two that provide a micro-computed tomography (micro-CT)-focused overview of available literature on various aspects of the root and canal morphology of the maxillary first permanent molar. The aim of this paper is to provide an overview of relevant aspects of the internal root morphology in different populations. The content is supported by illustrative micro-CT images and clinical cases or images.

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Keywords

Accessory canals, apical deltas, chamber canals, MB2, MB3, micro-CT, root canals, root canal configurations

Introduction

Root canal treatment implies the removal of irreversibly inflamed or infected tissues from the root canal system using mechanical and chemical disinfection techniques.[1,2] Cleaning and shaping the root canal are profoundly affected by the complexity of root canal morphology. Unsuspected root canal morphology may lead to the preservation of offending organisms and their by-products, which can cause treatment to fail.[2] The morphological complexity of the human molar, in particular, often leads to root canal anatomy being missed in the diagnostic phase, perforations and fractured instruments in the preparation phase and incomplete disinfection and removal of necrotic or inflamed tissues in the chemical phase.[3,4]root canals per tooth, root canal configurations, and frequency of isthmi and apical deltas in mandibular first permanent molars in an Indian population. Hundred and fifty mandibular first permanent molars were collected and subjected to clearing technique. The cleared teeth were examined in a stereomicroscope under 7.5x magnifications. The canal configurations were categorized using Vertucci's classification. Overall 94.6% of the mandibular first molars had two roots, and 5.3% had extradistal roots (distolingual root Maxillary molars can have a number of canals which are often challenging to locate without specialised equipment and proper magnification.[2,5-9]

The maxillary first molar has been identified as one of the most arduous teeth to treat endodontically because of its complex internal anatomy and the presence of additional canals.[5,7] One of these additional canals is a second mesiobuccal canal (MB2) located in the mesiobuccal root (MB).[6,8-11]and evaluate if there were any significant differences between initial treatments and retreatments. The teeth examined were 3578 first molars and 2038 second molars treated consecutively over a 5-yr period by six endodontists. Overall the MB2 canal was found in 2133 (60% The second mesiobuccal canal is often hidden by dentine ledges and sclerotic tooth structure, which makes it difficult to discover and treat and, unfortunately, it is often missed.[12,13] Figures 1-3 show the suggested clinical procedure to remove the covering dentine ledge to discover the MB2 canal system on maxillary molars.

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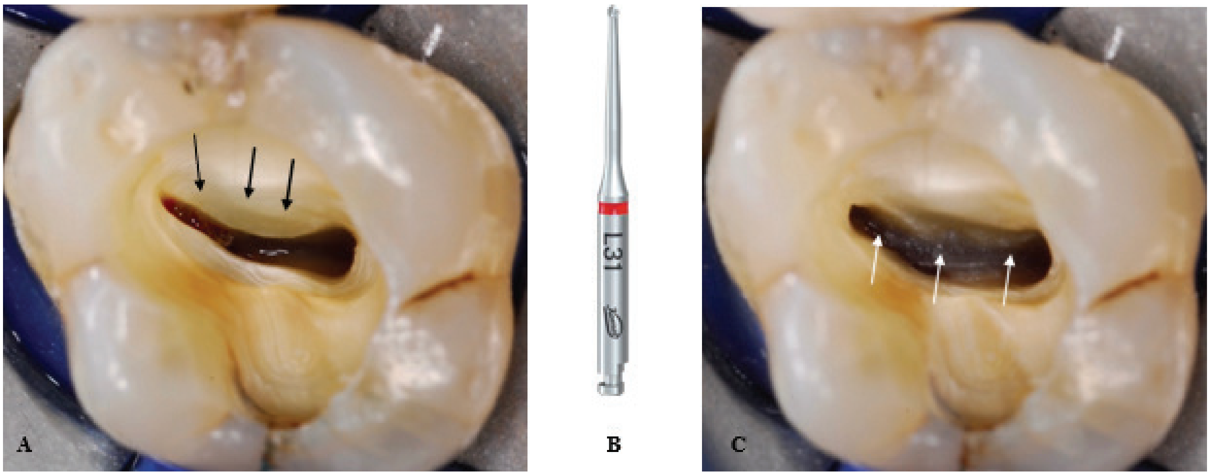

Figure 1: Access preparation and suggested instrumentation for dentine removal on a maxillary first molar; **(A)** Access cavity preparation on a left maxillary first molar after removal of a leaking amalgam restoration that resulted in secondary decay. Note the dentine ledge (black arrows) restricting the access into the MB canal and obscuring the canal orifice of the possible MB2 canal; **(B)** A size 010 EndoTracer bur (Komet) was used at a speed of 1500rpm under microscope magnification to remove the coronal aspect of the dentine ledge; **(C)** Dentine ledge removed until a smooth transition from pulp floor to root canal walls is visible.

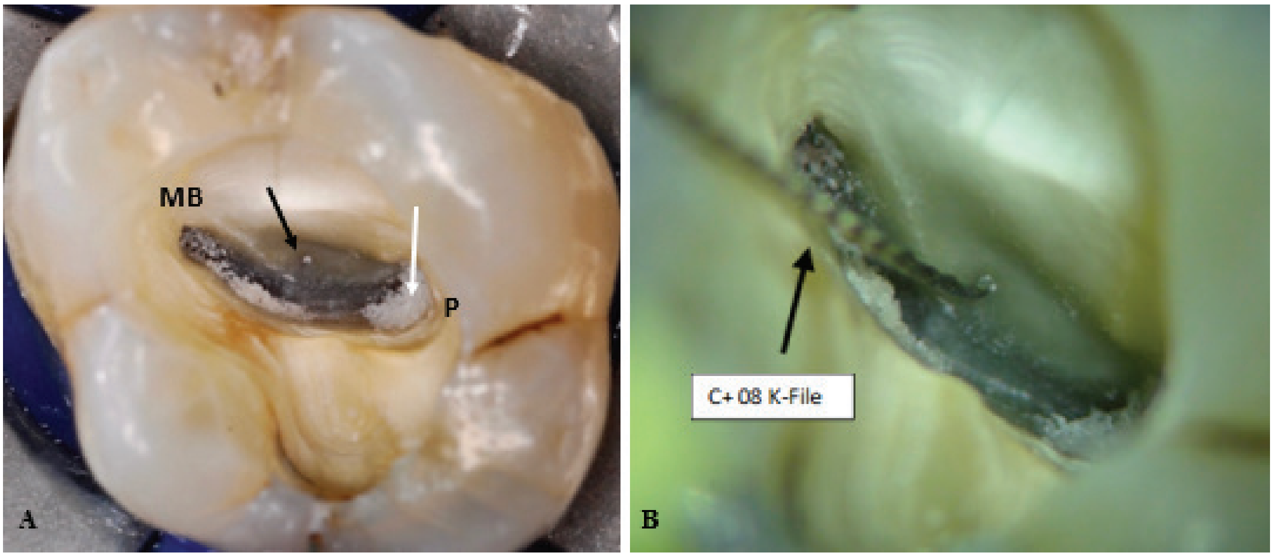

Figure 2: Identification and negotiation of the MB2 canal; **(A)** Improved access was obtained to the pulp floor revealing a groove (black arrow) running from the MB canal towards the palatal (P) canal orifice. A smaller size 008 EndoTracer bur (Komet) was used to through approximately 1.5mm deeper on the groove resulting in the appearance of the debris accumulation (white arrow) in the in MB2 canal orifice; **(B)** Size 08 C+ file (Dentsply Sirona) was used to start negotiation of the MB2 canal.

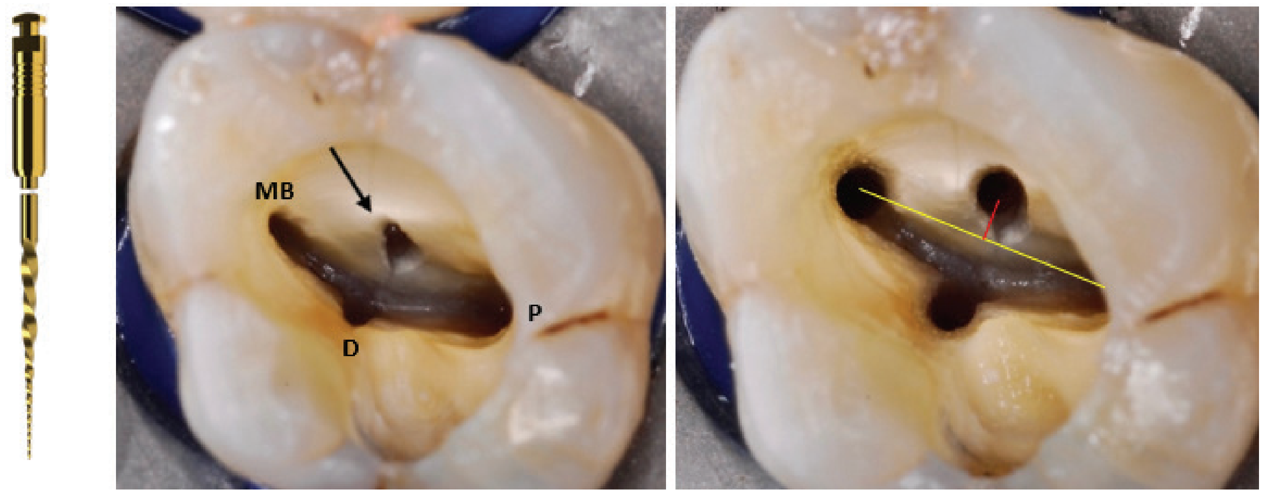

Figure 3: Cleaning and shaping the root canal system; **(A)** ProTaper Ultimate Orifice Opener (Dentsply Sirona) was used in a backstroke brushing motion to relocate the canal orifice in a more mesial direction to allow for easier canal negotiation; **(B)** Pulp chamber view after all the canal orifices were opened with the ProTaper Ultimate Orifice Modifier (Dentsply Sirona). Note the mesial relocation of the position of the MB2 canal orifice (arrow); **(C)** Pulp chamber view after all the canals were prepared up to size F2 ProTaper Ultimate (25/07) (Dentsply Sirona). Note the final position of the MB2 canal orifice is approximately 1.5mm-2mm more mesial from a line drawn from the MB and the P canal orifices.

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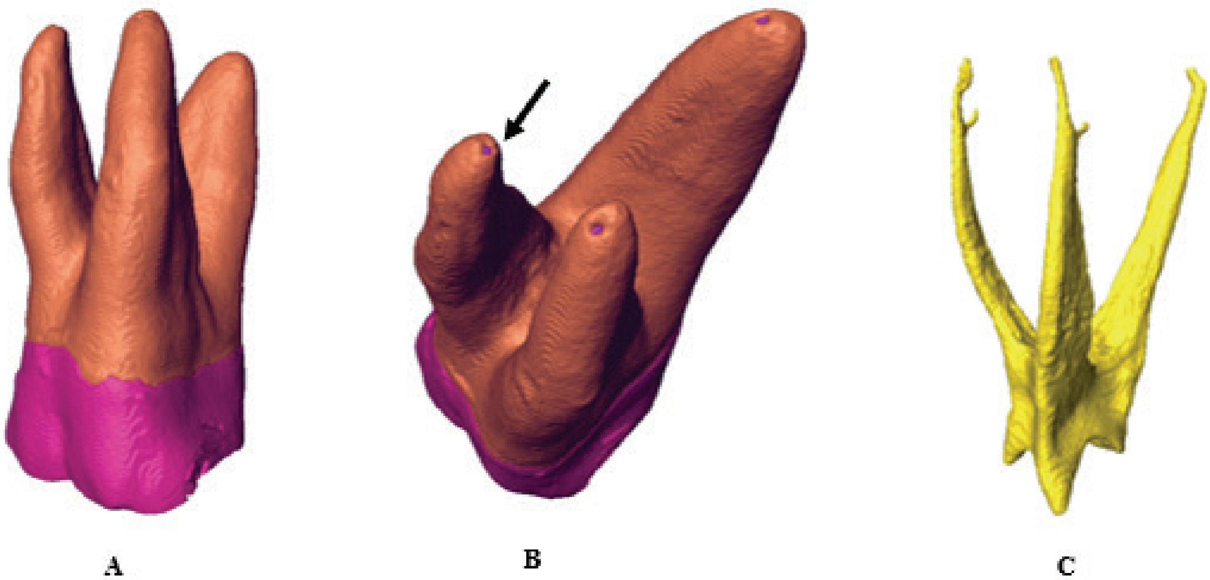

Figure 4: Micro-CT illustration of a typical maxillary first molar with three separate roots using Avizo software; **(A)** View from MB; **(B)** Rotation with a view from apical illustrating apical root canal exits and their apical foramen(s) (black arrow); **(C)** Virtually extracted pulp.

Additional canals can also be present in the other roots and if any of these remain untreated it can greatly influence the long-term survival of a tooth.[2,5] In addition, root canal configurations in maxillary first molars can be some of the most complex ones in the human dentition.[14] Apart from the main canals, a complex network of accessory canals can be located anywhere along each root canal.[15,16] Main canals can also terminate in apical deltas and the pulp floor can contain chamber canals with the potential to connect the pulpal space with the furcation region of a tooth.[2,17]

Many of the complexities and anatomical variations of the roots and canals of molar teeth could not be seen using conventional two-dimensional radiographs.[18] The introduction of micro-computed tomography (micro-CT) provided a non-invasive way to explore the morphology of roots and canal systems with accuracy and confidence.[19] Interestingly, the original use of micro-CT was not for dentistry but for industry.[20] Nielsen et al[19] were the first authors to use this technology to describe the internal and external root and canal anatomy of a maxillary first molar. It has since become the gold standard for morphological investigations and the most suitable method to study complex root canal morphologies to visualise fine detail.[21,22] In addition, modern software (for example Avizo[23]) can allocate different colours to enamel, dentine and the pulp for differentiation and each component can be virtually extracted (by labelling and segmentation), magnified and rotated (Figure 4).[23-25]

The aim of this paper is to provide an overview of available literature on clinically relevant aspects of the internal morphology of the maxillary first molars supported by illustrative clinical cases and micro-CT images. Authors have used different investigative techniques when studying root and canal morphology in different populations. The findings on various techniques are discussed in this paper, but special consideration is given to studies where micro-CT was used.

The second mesiobuccal canal (MB2)

Versiani, Sousa-Neto and Basrani[14] conclude that the presence of a second canal in the MB root is on average

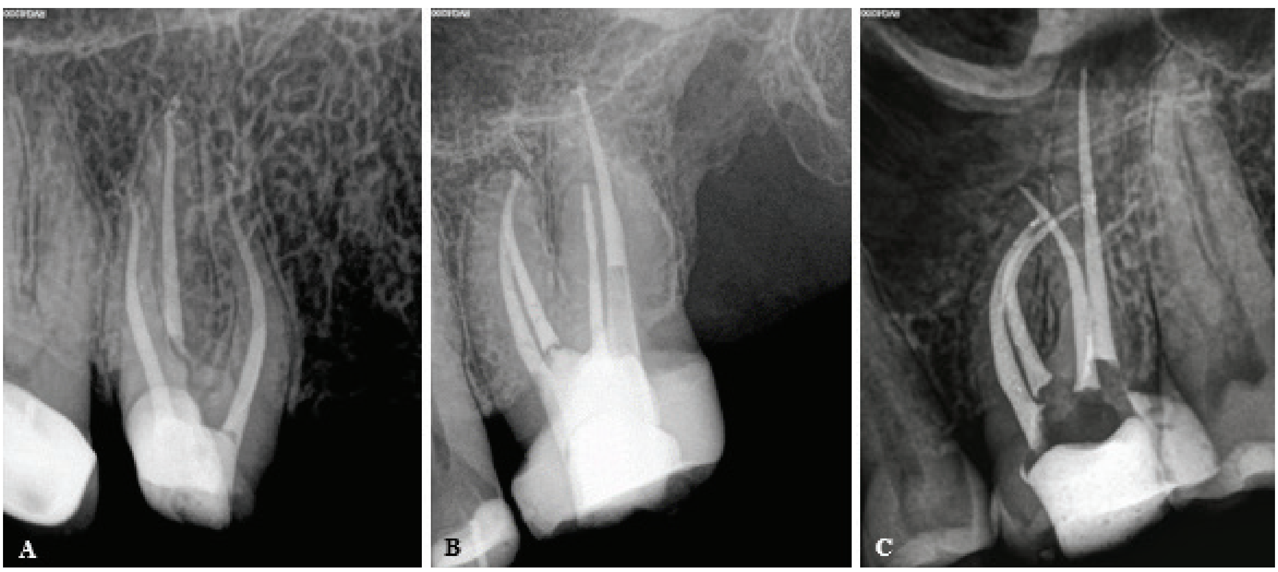

Figure 5: Different root canal configurations that may be present in maxillary first molars; **(A)** Right maxillary first molar that presented with only one MB canal; **(B)** Left maxillary first molar that presented with an MB and MB2 canal system that joined in the apical third of the root; **(C)** Left maxillary first molar that presented with an MB and MB2 canal system that had separate apical foramina in a severely curved MB root.

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Table I: Micro-CT studies reporting on MB2.

Author(s)	Year	Population	Number of teeth investigated	Prevalence of MB2 (%)
Park et al.[28]	2009	South Korea	46	80.0
Somma et al.[29]	2009	Italy	30	80.0
Gu et al.[30]	2011	South Korea	110	68.0
Verma and Love[31]	2011	New Zealand	20	90.0
Yamada et al.[32]	2011	Japan	90	55.5
Hosoya et al.[33]	2012	Japan	86	60.5
Domark et al.[34]	2013	USA	13	100
Kim et al.[35]	2013	South Korea	154	61.0
Lee et al.[36]	2014	South Korea	18	100
Tomaszewska et al.[13]	2018	Poland	110	64.2
Zurawski et al.[37]	2018	Brazil	6	95.8
Alfouzan et al.[38]	2019	Saudi Arabia	35	80.0
Camargo Dos Santos et al.[39]	2020	Brazil	96	87.5
Tonelli et al.[40]	2021	Brazil	90	69.4

60.4%. Prevalence, however, can vary between populations. In a recent worldwide cone-beam computed tomography (CBCT) observation involving 21 regions, the average prevalence was 73.8% – ranging between 48% (Venezuela) and 97.6% (Belgium).[10] In a Nigerian study, a group of authors used laboratory sectioning and direct observation on extracted first molars of unspecified individuals and an in vivo clinical investigation using radiographs of symptomatic patients. More MB2 canals were identified using the laboratory and direct observational technique (23%) than with the in vivo clinical observation (3%) in this study.[26] In a worldwide investigation, a prevalence of 62% was reported in Egypt using CBCT.[10] In South Africa, three CBCT studies reported a prevalence of 60.5%, 92% and 95.6% respectively,[10,11,27]age, side, and root configuration using in vivo cone-beam computed tomographic (CBCT but the population groups or backgrounds of the individuals were not specified in either study. In micro-CT-focused studies, authors have reported a prevalence of MB2 ranging from 60.5% to 100% (Table I). Figure 5 depicts three different clinical scenarios that were observed during clinical treatment of South African individuals.

The third mesiobuccal canal (MB3)

The MB root can contain an additional canal located between the MB1 and MB2.[41] Versiani et al.[14] reported an incidence of 0.1%, in all available literature reviewed. However, in the same year (2018) a global incidence of 5% for this type of morphology was reported from 12,200 maxillary first molars.[13] Focused research on this canal is limited with most findings discussed as case reports or incidental findings. Investigative methodologies also differ: for example, using a clearing and stereomicroscopic technique on extracted teeth, a high incidence of 11.3% was noted in Iranian individuals[42] while in Africa, using a combination of clearing, dyes and visual observation under magnification on extracted teeth of individuals from African descent, Rwenyoni et al.[43] determined that 0.5% of an Ugandan population had an MB3. No studies reporting on the presence of the MB3 in South African individuals were identified but Figures 6 and 7 show the clinical procedure that was followed to locate and treat the MB3 in a maxillary first molar in a South African individual.

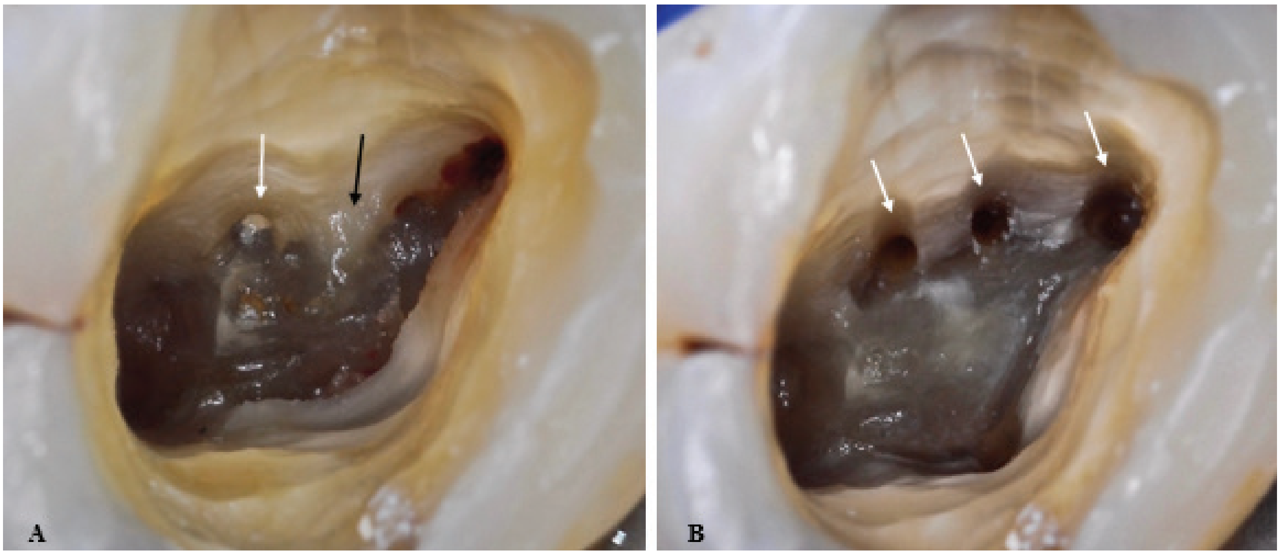

Figure 6: A right maxillary first molar that presented with an MB3 canal; **(A)** High-magnification view of the pulp chamber floor. Note the evidence of a dentine ledge (black arrow) and necrotic pulp tissue in a canal orifice visible close to the P canal orifice (white arrow); **(B)** After removal of the dentine ledge with EndoTracer burs (Komet), three MB root canal systems (arrows) were discovered in the MB root.

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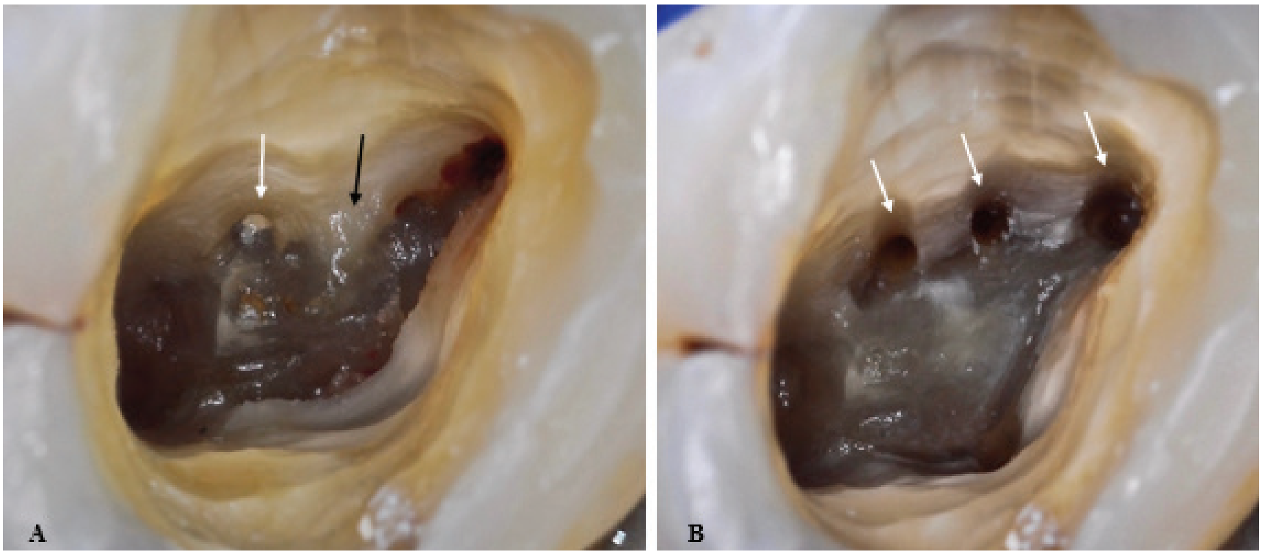

Figure 7: Clinical procedure for cleaning, shaping and obturation of a maxillary first molar with three MB canals; **(A)** Pre-operative periapical radiograph of a non-vital, right maxillary first molar that required root canal treatment; **(B)** High-magnification view of the pulp chamber floor showing the location of three mesiobuccal canal systems in the mesial root after canal preparation with the F2 ProTaper Universal System (Dentsply Sirona); **(C)** Postoperative periapical radiograph after obturation of the five root canal systems. Note that the MB2 and MB3 canals joined in the midroot area to exit in a combined apical foramen next to the MB1 canal, which was a separate system.

Table II. Micro-CT studies identified reporting on MB3.

Author	Year	Population	Sample size	Prevalence (%)
Park et al.[28]	2009	Canada (Koreans)	46	6.5
Gu et al.[30]	2011	South Korea	110	8.2
Verma and Love[31]	2011	New Zealand	20	10.0
Kim et al.[35]	2013	South Korea	154	12.3
Briseño-Marroquín et al.[21]	2015	Germany	179	5.0
Alfouzan et al.[38]	2019	Saudi Arabia	35	17.1
Camargo et al.[39]	2020	Brazil	96	3.1

Micro-CT studies on the MB3 are limited but some have been identified. Ordinola-Zapata et al.[41] report a figure of 10% in a Brazilian subpopulation using micro-CT. Other identified micro-CT studies reporting on this type of morphology in different populations are summarised in Table II.

Additional canals in the DB and P roots

Most of the reports available mentioning additional canals in the DB and P roots used techniques which included clearing and staining, traditional radiographs with clinical investigation and CBCT,[44-47] and findings ranged between 0 and 9.5% for the DB root and 0 and 4.5% for the P root. A global study reported an incidence of 1.4% and 0.7% of additional canals in the DB and P roots respectively.[14] In a CBCT study, Tian and co-workers[48] found figures in agreement with the suggested global range; approximately 0.2% of Chinese maxillary first molars had an additional P canal and 0.4% had additional distal (D) canals. In Africa, specifically in Uganda, the researchers did not find any additional canals in the P root but 2.3% of the D roots contained an additional canal.[43] Similarly in Nigeria, Abiodun-Solanke et al.[26] found an additional P canal in 1% of their sample using visual observation and surgical loupes. No studies could be identified reporting additional canals in the DB or P root in South African individuals. Although South African studies are not available, clinicians have probably treated these challenging root canal morphologies on occasions. Figure 8 shows a clinical case with an additional canal in the P root in a South African individual.

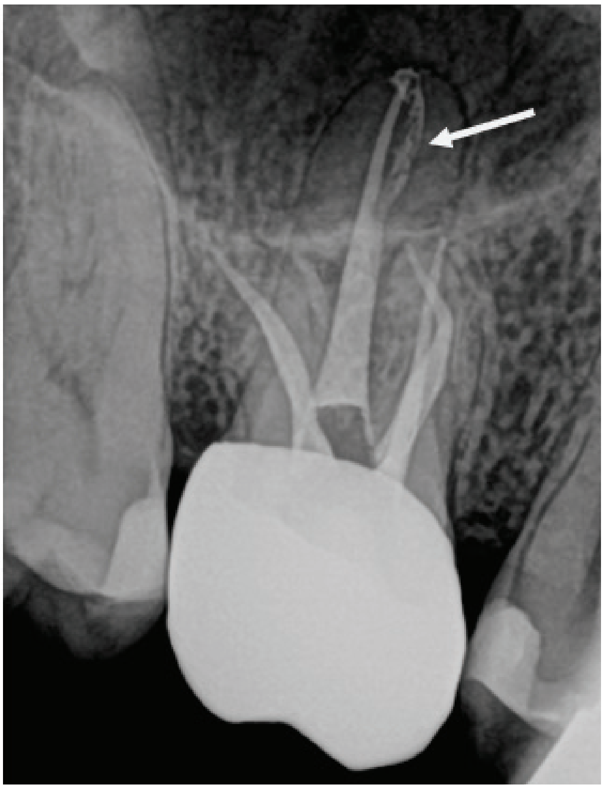

Figure 8: Right maxillary first molar that presented with an additional canal in the P root (white arrow) that bifurcated from the main canal at the midroot level. Note the two separate MB root canal systems in the MB root.

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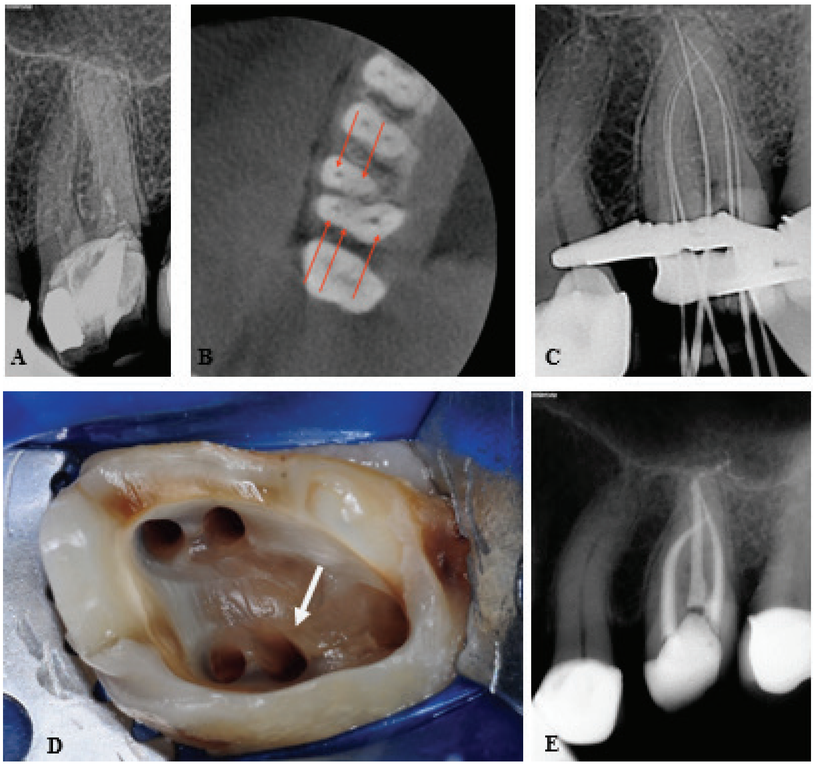

Figure 9: Clinical management of a maxillary first molar with an additional DB canal; **(A)** Pre-operative periapical radiograph of a left first maxillary molar that presented with an emergency root canal treatment; **(B)** Axial slice on a CBCT scan revealed the presence of an MB, MB2, P, D and an additional distobuccal (DB) canal system; **(C)** Periapical radiograph to confirm the working length of the five-root canal systems; **(D)** High-magnification view of the pulp chamber showing the additional canal in the DB root (white arrow) after canal preparation; **(E)** Postoperative periapical radiograph after obturation with temporary restoration.

Figure 9 depicts a clinical case where an additional canal was present in the DB root of a South African individual.

Global studies that reported on results on additional D or P canals using micro-CT exclusively are limited and there are none in African populations. Briseno-Marroquin et al.[21] found an incidence of 1.2% for an additional D canal in a German sample. In a Burmese (Myanmar) study no additional P canals were found, but of the DB root 13.86% contained multiple canals in their sample of 101 first molars.[49] Matsanuga et al.[50] also found no additional canals in the P root of a Japanese sample. A later study in Japan focusing on the DB root found that 2% of DB roots had additional canals.

Variants of canal numbers

Apart from the MB2, MB3 or an additional DB or P canal, maxillary first molars may contain more than five canals in total. Variants that deviate from the expected three or four canals in these teeth where investigators used micro-CT exclusively are limited and none was identified in African populations. Teeth with a single canal were reported in 0.06% of a Chinese population using CBCT and a large sample (n=1,558).[48] Two-canalled configurations were found by the same author in 0.8% of the sample. These authors also found 0.5% of teeth with six canals in total, made up of different combinations of MB, DB or P canals. A few reports are available on first molars with six canals. By using radiographic observation and clinical treatment under magnification, Albuquerque and co-workers[51] treated a tooth with complex root canal morphology. Zheng et al.[46]4,22]]},”issued”:{“date-parts”:[[“2010”,9]]}}],”schema”:”https://github.com/citation-style-language/schema/raw/master/csl-citation.json”} used CBCT during their investigation and found 0.3% of teeth with six canals in a Chinese population. There are other reports on six canals available.[52,53] Teeth with seven canals were clinically treated under magnification assisted by using radiographs and CBCT technology.[54,55] A report is also available of treating an eight-canal tooth.[56] No micro-CT specific reports giving an account of first molars with one, two or more than five canals could be identified in Africa or South Africa.

Accessory canals

According to Ahmed et al.[57] an accessory canal is a small patent, blind or looped canal leaving the main canal that usually (but not always) communicates with the external root surface or furcation area and encompasses what were previously known as lateral canals. The presence of accessory canals has been investigated for several years in different populations using a variety of techniques. In an Irish population, Shalabi et al.[58] determined that the P root had the most accessory canals and these canals ranged between one to five per root. Most were in the apical third. These authors used a clearing technique during their investigation. Sert and Bayirli[44] used staining with dyes on extracted teeth in a Turkish population and found that all roots of all teeth in both males and females contained lateral canals. They were present in either the cervical, middle or apical third of the root. In Uganda it was determined that the MB root had the most accessory canals after using a similar staining technique on their extracted teeth.[43]

In micro-CT studies, Yamada et al.[32] confirm findings from the Ugandan study: the MB roots of their Japanese population sample contained the highest number and the most diverse root canal morphology. A similar finding was by Briseño Marroquin et al.[21] in a German population. In a Myanmar study the authors found 240 total lateral canals in 101 maxillary first molars, with 56.67% of these in the MB root, 23.75% in the DB root and 19.58% in the P root.[49] These authors determined that the MB1 canal contained one accessory canal in 26.3% of cases, one accessory canal was present in 12.3% of cases in the DB canal and 9.5% in the P canal. The same authors found that the MB2 canal rarely had a single accessory canal.[21] In one Brazilian study several accessory canals, isthmuses and foramina were noted in the apical region in particular of the MB root.[41]

In a study on a Brazilian subpopulation also focusing on the MB root, it was noted that 47.9% of the sampled teeth contained accessory canals and the majority of these were also in the apical region (76%).[39] A South Korean population had similar accessory root canal morphology in the apical region of the same root.[28]

In another micro-CT study on Brazilian individuals, it was found that the P root contained several accessory canals (25%).[59] A Minnesota study investigating maxillary first and second molars found that at least 40.4% of the P roots contained at least one accessory canal and most of these (74.1%) were in the apical 3mm. Unfortunately, the study did not make a clear distinction between first and second molars.[60] Similar findings were reported in a Chinese subpopulation.[61] A Japanese study focused on the DB root and found that 27% of the sample contained accessory canals and the vast majority were located apically (88.9%).[62] Other authors in Brazil, Taiwan and Japan reported similar findings by investigating either the P, MB or all roots.[59,63,64]

Micro-CT studies reporting accessory canals in African and South Africa populations could not be found. However, Figure 10 illustrates clinical cases of treatment of South African individuals with accessory canals in various roots.

Chamber canals

Accessory canals can also be present in the pulp chamber in the form of furcation canals in the furcation region, which can create a potential pathway between the pulp and the periodontal ligament space (PDL).[17] In a Turkish study using a stereoscopic technique, the pulp floors of 50 maxillary first molars were investigated and it was found that patent furcal accessory canals were present in 12 teeth (24%).[65] Although investigations focusing on the presence of furcation canals using micro-CT are rare a more recent micro-CT study using extracted teeth from Egypt and Germany, furcation canals were identified in 2.8% of the sample teeth (n=179). The authors distinguished between inter-radicular canals where the pulp chamber communicated with the PDL space and those with blind endings (diverticula). Inter-radicular communications were found in 0.6% of the 2.8% and diverticula made up the rest (2.2%).[17] To the best of the authors' knowledge, the prevalence of chamber canals has not been reported in African populations.

Apical deltas

According to Ahmed et al.,[57] an apical delta or an apical ramification is a root canal network at or near the root apex where the main root canal divides into more than two accessory canals. The presence of apical deltas has been reported in various populations, Sample size and the use of newer modalities such as micro-CT did not seem to affect the prevalence of apical deltas in a predictable way. In a large sample comprising 2,800 teeth conducted in Turkey, deltas were observed in all the roots of both males and females using a staining technique, but a higher number were reported in females. In this study, it was determined that the P root contained the most, followed by the DB and MB roots.[44] However, when also using a clearing and staining technique, in the Ugandan study already mentioned, an incidence of 5% was reported and 25% in an Indian subpopulation.[66] The use of micro-CT, for instance in the study in Brazil, could not demonstrate apical deltas in all roots as only up to 12% apical deltas were observed in first molars.[67] In a Chinese micro-CT study, 15% of teeth had apical deltas and most were located in the MB root, compared to 11.2% of the DB (1.7%) and P (1.1%) roots.[68] Unfortunately, in the Chinese study no distinction was made between first and second molars, so one can only speculate on the incidences of each molar group. The prevalence of apical deltas in South African populations is not known and no investigations were found.

Root canal configurations

Root canals can follow distinct paths within a root and calculating root canal configurations provides valuable information on the internal root and canal morphology of teeth.[69] Although a number of classifications have been suggested, the Vertucci system is considered by many to be the most appropriate and several authors have used it to determine root canal configurations in the maxillary first molar.[27,43,7–72] Similar findings as initially described by Vertucci using a clearing and staining technique on molars

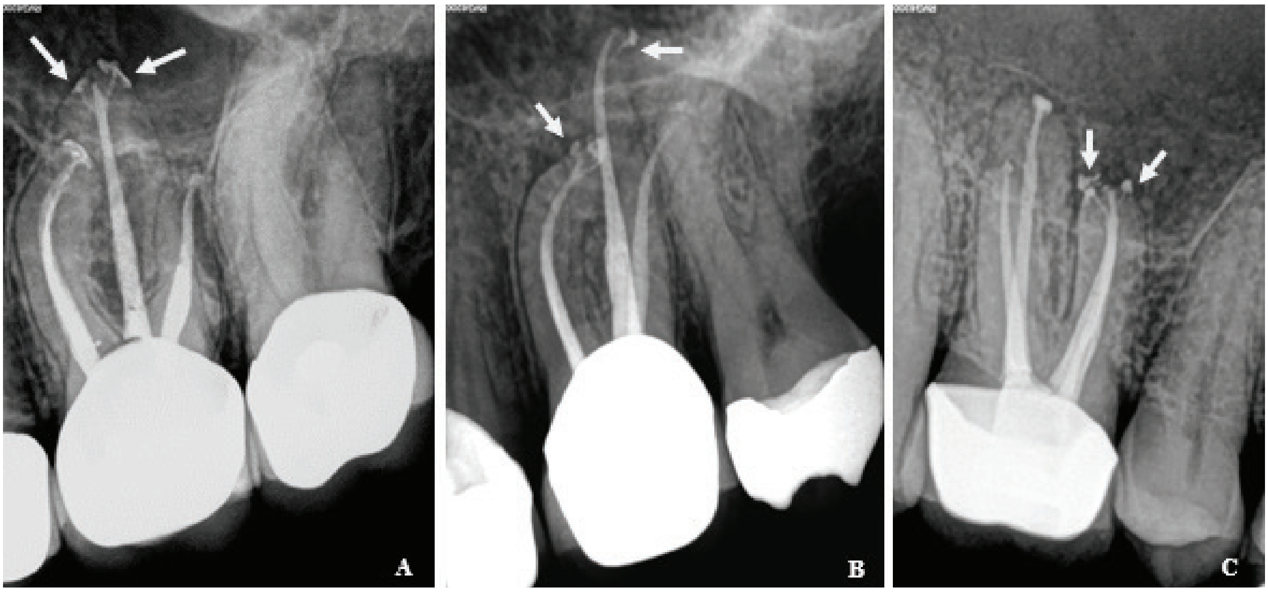

Figure 10: Accessory root canals in maxillary first molars; **(A)** Left maxillary first molar that presented with two patent accessory canals (white arrows) in the P root branching off from the main root canal system in the apical third; **(B)** Left maxillary first molar that presented with one patent accessory canal in both the MB and P root (white arrows), branching off from the main root canal system in the apical third; **(C)** Right maxillary first molar that presented with two patent accessory canals in the MB root (white arrows), branching off from the main root canal system in the apical third.

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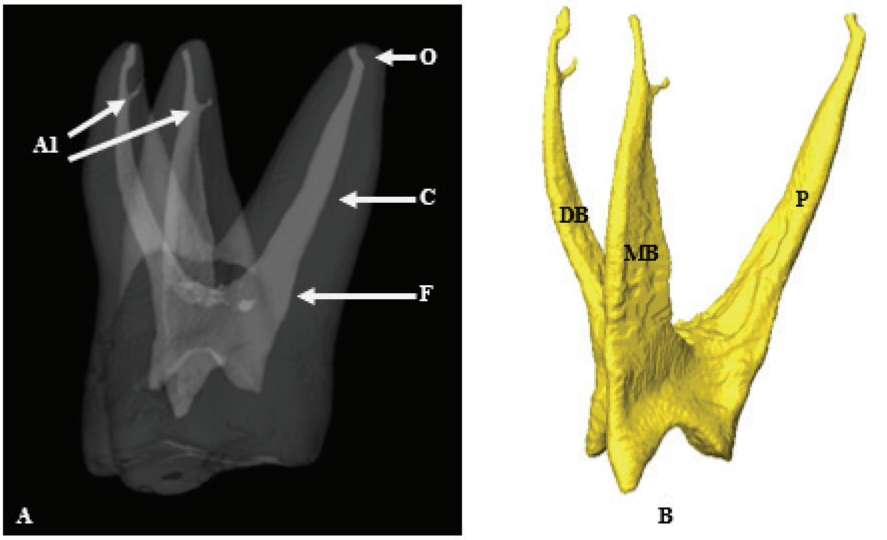

Figure 11: Root canal configuration calculation according to Ahmed et al.[16,58]; **(A)** Root canal configuration of a right maxillary first molar. In the illustrated images, all root canal systems have a single canal with a single orifice (O). All main canals also follow a singular pathway (C) on their way to the apex with a single apical foramen (F). In both the MB and DB systems, a single patent accessory canal is present in the apical third (A1). The configuration for this tooth is ^{3}MFM M$^{1(A1)}$ D$^{1(A1)}$ P^{1}, indicating a three-rooted maxillary first molar with its internal root canal morphology; **(B)** Virtually extracted pulp from the same tooth displaying the root canal system including main and accessory canals.

extracted from American individual, have been reported on various populations and modalities, including on a South African CBCT sample and in micro-CT studies.[27,31,95,59,43,59,70] Vertucci determined that the root canal systems in the DB and P roots contain a type I configuration (one canal from orifice to apex), while the MB root is more diverse. In the MB roots, Vertucci et al.[70] described types I, II (two canals joining into one at the apex) and IV (two separate canals from orifice to apex), Kyaw Moe et al.[49] found all the Vertucci configuration types, Kim et al.[35] all the Vertucci classification types except type I, while Rwenyonyi et al.[43] found all the Vertucci classification types except type VIII (three separate canals from orifice to exit) while also types I, II and V in the D root.

The Ahmed classification system has recently been introduced.[16] In this system, calculations are determined by following each root canal from the orifice to its pathway and eventual foramen (O-C-F). The system also allows the inclusion of complexities (Figure 11).

Most studies identified used CBCT as their investigative method on different teeth from various populations.[73–75]the root number and canal configurations were described using the classification systems devised by Vertucci (1984 However, studies reporting on this new classification system in maxillary first molars are scarce. Using CBCT and the Ahmed et al. classification system, Mirza et al.[76] determined that most of the molars in a Saudi Arabian sample contained either ^{3}MXFM MB$^{2\text{-}1}$DB^{1}P^{1}, ^{3}MXFM MB^{2}DB^{1}P^{1} or ^{3}MXFM MB^{1}DB^{1}P^{1} configurations. This indicates that most of the three-rooted molars had single canals from orifice to apex in the DB and P roots and had either two separate canals, two joining into one or a single canal in the MB root. No micro-CT studies were found in which the Ahmed system was used to calculate root canal configurations to include complexities, for example accessory canals and deltas in different populations.

DISCUSSION

It is apparent that root and root canal morphology can differ between populations because of genetic and external factors.[73,77]the root number and canal configurations were described using the classification systems devised by Vertucci (1984 It is important that clinicians are aware of any variations as they can greatly influence endodontic treatment outcomes. Any missed roots and root canals increase the risk of treatment failure as they can harbour infected or irreversibly inflamed tissues.[2,78]

Methodologies, study designs and sample sizes differ between investigations and care should be taken with interpretation.[79,80] For example, one author found the MB2 canal in all maxillary first molars but the sample included only 13 teeth. Staining, CBCT and other techniques have been used to investigate root and canal morphology, but different results were noted depending on populations and the investigative techniques used. Micro-CT, the most commonly used methodology to investigate internal root morphology, has the ability to identify the finest detail, often missed with other methods.[16,41,81] It can be speculated whether micro-CT would have provided different results in the studies where CBCT, staining, radiographs and other techniques were used. The clinical applicability of CBCT cannot be denied, but its use can be limiting in observing fine root canal morphology. However, it is sufficient to report on external and internal root and canal morphology without relying on the inclusion of fine detail.[15,57]

Most maxillary first molars contain three or four canals. Although figures vary, an estimated guide is that three canals can be present in roughly 30% to 40% of teeth and 60% to 70% can have four canals.[14] The presence of the MB2 canal has been identified as one of the reasons for treatment failure, making the maxillary first molar one of the most challenging teeth to treat endodontically.[6,9] The MB2 canal is often hidden by dentine ledges and sclerotic tooth structure, which makes them difficult to discover, and unfortunately they are often missed. The presence of this canal is one of the main reasons why this tooth has the highest endodontic failure rate of all treated teeth.[82,83] Dental practitioners may not have access to specialised equipment such as proper magnification and illumination.[41] Different findings have been noted globally in different populations and the discovery of these canals has been a focus of research for years. Methods of investigation include radiographic[84] clearing and staining,[85]supporting and complementing commonly applied clearing technique, using access cavity modification and the pulpal groove deepening method. Three hundred and ninety eight extracted intact human maxillary first molars were included in this study. Firstly, modified rhomboidal shape access cavities were prepared

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then, the developmental groove between the mesiobuccal and the palatal canals was deepened 1 mm with a round slow speed bur. Indian ink was injected into both the canal orifices of mesiobuccal roots and into the groove between mesiobuccal and palatal canals, using a 22 gauge syringe. Then the clearing technique was applied. The incidence of one canal was 30.90 %, two canals was 62.07 %, three canals was 7.03 %. In twenty five (6.28 % CBCT[10] and micro-CT, with incidences ranging between 23.3% and 97.6%.

In Africa, studies from Egypt[10] and Nigeria[26] report incidences of 62% for the MB2 canal using CBCT and a lower incidence of 23% using sectioning and magnified observation with surgical loupes. The number of MB2 canals may have been higher if three-dimensional techniques (CBCT or micro-CT) had been used in the Nigerian study. It is interesting to note that three South African CBCT studies reported findings of 60.5% Witwatersrand (Gauteng)[27], 92% Pretoria (Gauteng)[11](100 female and 100 male patients and 95.6% Durban (KwaZulu-Natal)[10] respectively. In all three, the teeth were collected from mixed populations. Genetic and/or external factors could have contributed to the difference in prevalence between different populations within one country. External factors could be associated with soco-economic status or geographic location. Differences between scan resolutions,[0], experience of the researcher or the size of the sample in these three studies could also have played a role.

Apart from the MB2 canal, the MB root can contain more than two canals in the form of a third, namely the MB3. Although not as common in most populations, the MB3 canal can still result in treatment failure if not negotiated. The incidence can range anything between 0.1% and 17%, according to reports available. In a Ugandan population the prevalence was 0.5%[43] and in a Saudi Arabian sample it was 17%.[38] In the Saudi Arabian investigation the sample size was relatively small (35 teeth); a larger sample size could have revealed different results. The use of staining techniques can have certain disadvantages. It can be difficult to remove all blockages, debris and vital tissues from the entire root canal system during preparation of teeth to allow the flow of dyes, and this will hinder the identification of morphology.[32] Any additional root canals in the Ugandan study could have remained unseen, whereas Alfouzan et al.[38] used micro-CT in their Saudi study. The smaller sample of the Saudi study might also have influenced results.

Additional canals can also be present in the DB and P roots and incidences may vary between 0 and 9.5% for the DB root and 0 to 4.5% for the P root. In much rarer cases, one, two, six, seven and eight canals have been reported. Clinicians should be aware of the possibility of internal morphology outside the expected findings and careful clinical observation and radiographic investigation are required. The clinical application of CBCT has been well documented[11,14,73](100 female and 100 male patients and it could allow proper pre-operative planning and diagnosis if available. Although the prevalence of root canals may vary, clinicians should expect to find additional canals until proven otherwise. Accurate predictions may also be impossible, but morphological studies can give clinicians a degree of predictability within populations.

Between 74% and 80% of teeth diagnosed with apical periodontitis contained biofilms of organisms in the apical part of the root canals and in many cases within accessory canals.[86] Reports confirm that accessory canals are present in most roots and most frequently in the apical portion.[39,43,44,58] However, discrepancies have been noted in terminology referring to accessory canals. Authors mention accessory canals, lateral canals and secondary canals, which has created some confusion.[87,88] For example, the description of the apical delta according to the AAE glossary is a root canal morphology where the main root canal terminates in multiple accessory canals at or near the apex.[89] The question is how many accessory canals define an apical delta, and where exactly is "at or near the apex"? Recently, a group of authors suggested a standard description for accessory root canal branches (accessory canals, deltas and chamber canals) which encompasses other terminology.[57] These authors defined an apical delta where more than two accessory canals are present in the proximity of the apex. The current consensus is that a delta includes three or more ramifications at or near the apex of a root.[31,57,68,90]

The presence of accessory canals and deltas can also play an important role in treatment outcomes. These additional types of root canal morphology are common in human dentition and connect the root canal system to the PDL space by encapsulating blood vessels during the Hertwig root sheet (HERS) development stage.[61] They can also be very difficult to reach with root canal instrumentation and to disinfect with chemicals. This could prove problematic, as bacteria and their by-products can travel from infected root canals to PDL spaces causing disease, or periodontal disease can affect the pulpal space through these channels.[86] Apical deltas can provide multiple portals of communication between the root canal network and the PDL space which treating clinicians should take note of. Vigorous mechanical and chemical regimes should be followed to achieve proper disinfection.

Investigative methodologies differ but the main methon used to observe apical deltas is the clearing technique.[68] Interestingly, apical deltas were noted in 5% of cases in Uganda but 25% in an Indian subpopulation using a similar technique of staining.[43,66] Differences can be attributed to population group or even operator technique and sample size. Micro-CT studies focusing on apical deltas are not common. In one micro-CT study, it was determined that in Chinese individuals, the MB root can contain the highest number of apical deltas.[68] Similar micro-CT observations were made by others in different populations and the MB root was also identified as the one with the most complex internal morphology, including the presence of accessory canals and deltas.[29,31,41,91]

The other type of accessory canal that can be present is a furcation or chamber canal. These canals can be significant clinically and cause caries-free teeth to become irreversibly affected if periodontal breakdown is present. Causative micro-organisms can gain entry to the root canal space through these channels and vice versa.[92] This type of morphology has been investigated using different methods which include radiographic,[93] clearing and dyes[94] and scanning electron microscopy,[95] but micro-CT investigations are limited. One group of investigators conducted the first micro-CT study in 2022 and described the canals as either patent (inter-radicular) or blind ending (diverticula). Any of these can harbour organic material which can cause

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inflammatory reactions.[17] Treating clinicians should be mindful of the presence of these root canal morphologies. A proper three-dimensional seal of the pulpal space including the pulp chamber floor during endodontics is vital to close all possible portals of communication and avoid failure and a recurrence of infection.

Through the years authors have incorporated root canal classification systems into their study designs to identify common root canal patterns and their variants. Knowledge of root canal configurations can be beneficial to treating clinicians for diagnostic and treatment planning purposes during endodontics. One of the earliest classifications was described by Weine et al.;[96] it contained three basic configuration types and since then systems have evolved to include more complex configurations. It was clear from an early stage that not all complex configurations could fit into just a few simple categories. As a result, new systems have been suggested or additions made to current systems during investigations.[21,44,70,97,98] Despite new classification types and modifications, shortcomings are still present, for example the inability to include detail.[69]

The Ahmed et al.[16] classification system is a welcome addition as it made it possible to include fine detail in calculations, such as accessory canals, apical deltas and complex connections between canals.[15,16] Its clinical and academic applicability has also been described, including its merit in training undergraduate and postgraduate students.[99,100] However, the authors themselves mention that the inclusion of fine detail, while beneficial, adds complexity and the risk of confusion among researchers.[81] It seems that the authors faced similar challenges during the development to those that other authors experienced in the past. The number of subjective viewpoints, which could make comparisons between studies inaccurate, should be reduced.[81] The current study identified no micro-CT studies where authors included accessory canals, chamber accessory canals or apical deltas in their calculations on any tooth using the Ahmed et al. classification system. The authors therefore believe that a modification to the Ahmed classification system is required that allows the inclusion of fine detail in configurations without the risk of further confusion and complexity. Clear guidelines and reference to applicable landmarks are also required. A solution will allow standardisation of comparisons of complex configurations of various teeth in different populations.

In conclusion, the internal root canal morphology of the maxillary first molar can be highly complex and the prevalence of the MB2, MB3, additional P and D canals, accessory canals, chamber canals and apical deltas varies across populations. Investigative studies using micro-CT could be beneficial in evaluating internal root and canal morphology for diagnosis and treatment planning. There is also a need to modify or revise classification systems using the Ahmed et al. criteria to include complex configurations. Studies within Africa and South Africa are limited and no micro-CT studies that indicated a prospect of future investigations were identified.

Declaration

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Conflict of interest

The authors declare that there is no conflict of interest.

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