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

Part 2: Internal root morphology

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ABSTRACT

The endodontic intervention of the mandibular first molar can be challenging. Once root canals or any portion of them remain undiscovered and untreated, the risk of treatment failure greatly increases. The consensus is that mandibular first molars may have three or four main root canals. However, variations have been noted between populations, which include the mid-mesial canal (MM) and the mid-distal canal (MD). Authors have also attempted to classify root canal configurations to identify common patterns for diagnostic and treatment planning purposes. The introduction of micro-computed tomography (micro-CT) to root and canal morphological studies revolutionised observation of complex root canal anatomy in three dimensions and high definition. This paper is the second of two providing an overview of literature on various aspect of the external and internal root and canal morphology of the mandibular first permanent molar. The aim is to provide an overview of relevant aspects of the internal root morphology of the mandibular first molar in different populations. The content is supported by illustrative micro-CT images and a report on clinical cases where anomalies have been treated.

Keywords
Accessory canals, apical deltas, chamber canals, micro-CT, middle-mesial canal, middle-distal canal, root canal configurations

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INTRODUCTION

During root canal treatment clinicians aim to remove irreversibly inflamed or infected tissues from the entire root canal system using a combination of mechanical and chemical disinfection techniques.[1,2] Treating clinicians find molars particularly challenging to treat due to the complexity of their root and root canal morphology. Aspects of the internal morphology of the root canal can easily be overlooked during the diagnostic phase but, even if they are discovered, they can be challenging to treat. Once root canals or any portion of them remain undiscovered and untreated, the risk of treatment failure greatly increases.[2-4]

The mandibular first molars are often mistakenly identified as primary teeth, leading to their neglect and an increase of carious pulpal involvement requiring root canal treatment.[5] According to the literature, the treatment of human mandibular molar teeth can be quite complex and there are several variants in the number of canals and roots.[2,6,7] The consensus is that mandibular first molars may have three or four main root canals.[7] Figure 1 depicts different clinical scenarios that may be encountered during treatment of these molars where three or four canals are present.

However, variations have been noted between populations.[8-11] Barker *et al*. and Vertucci and Williams[12,13] were some of the first investigators to discover an additional mesial canal in the mesial root; there can also be additional canals in the distal root.[14] Authors have also attempted to classify root canal configurations to identify common patterns for diagnostic and treatment planning purposes.[15,16]

Authors used clearing and staining techniques to explore root and canal morphologies[13,15] and radiographs.[17] More recently, high-resolution three-dimensional (3D) techniques

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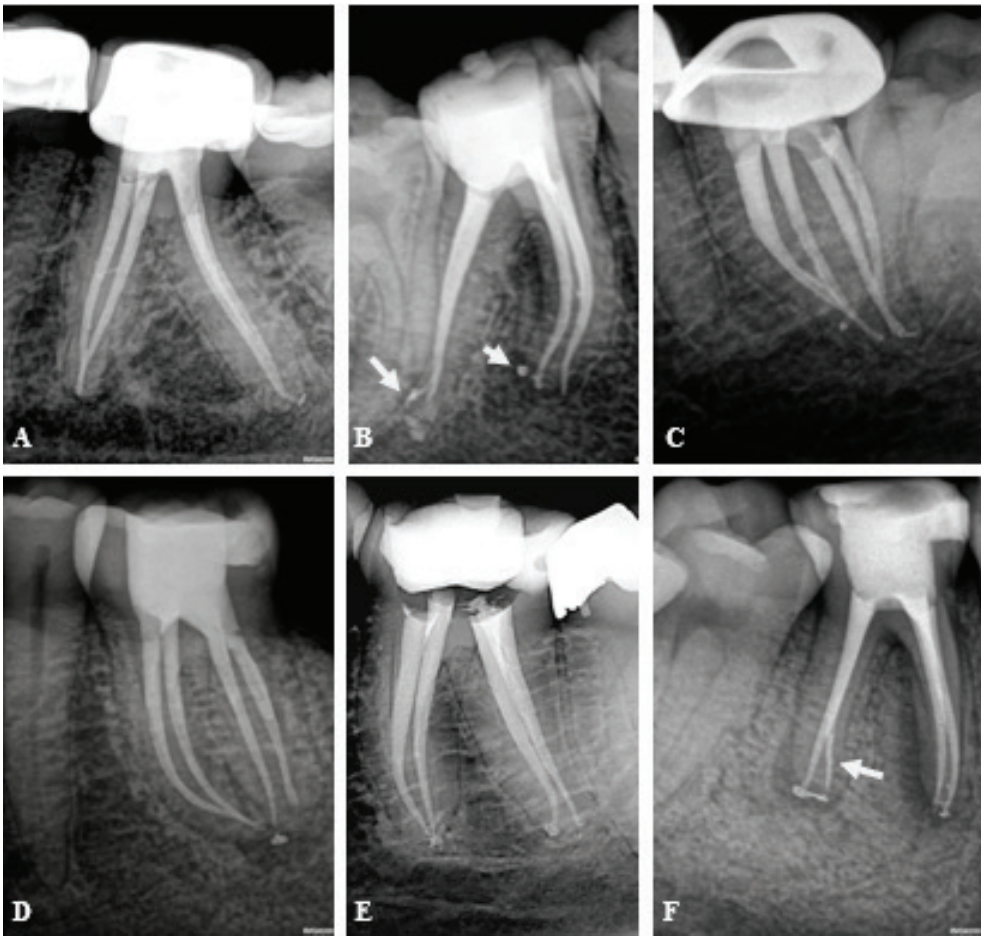

Figure 1: Different root canal configurations encountered during endodontic treatment of mandibular first molars; **(A)** Two mesial root canal systems joining in the apical third of the mesial root and a single distal root canal system; **(B)** Two separate mesial root canal systems and one single distal root canal system with an accessory canal in the apical third of the mesio-lingual (ML) and distal canals (white arrows); **(C)** Two separate mesial and two distal root canal systems joining in the apical thirds of the mesial and distal roots respectively; **(D)** Two mesial root canal systems joining in the apical third of the mesial root and two canal systems in the distal root that are separate; **(E)** Two separate mesial and two separate distal root canal systems; **(F)** Two separate mesial canals and a distal canal that bifurcates in the apical third (white arrow).

have been used such as cone-beam computed tomography (CBCT) and micro-computed tomography (micro-CT).[18] Micro-CT revolutionised the way root and root canal morphology are observed with the superior accuracy it offers. The pixel resolution of micro-CT data allows the detection of the finest root canal detail and can also detect calcifications at different levels of the root canal system.[19] Nielsen *et al.*[19] pioneered this technology in 1995 by describing the root and root canal morphology of a maxillary first molar. Since then it has become a popular method to describe complex morphological features in human dentition.[7,19-22] With the use of software (for example Avizo[23]), a tooth can be viewed from different angles, individual components can be isolated and colours can be allocated to the enamel, dentine and pulp to increase diagnostic accuracy (Figure 2).

The aim of this paper is to provide an overview of available literature on the root canal morphology of the mandibular first molar supported by illustrative images and clinical cases. Although a variety of investigative methods are used to report on different populations, the focus is on the use of micro-CT.

The middle-mesial canal (MM)

An additional canal can be present in the mesial root of

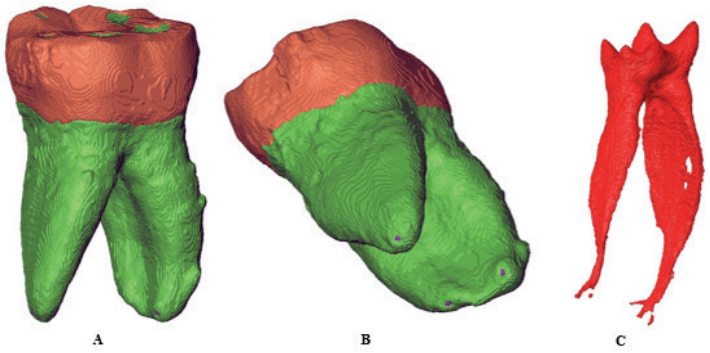

Figure 2: Micro-CT display of a typical mandibular first molar; **(A)** Virtually extracted right mandibular first molar using Avizo[23] viewed from buccal; **(B)** Apical view of the same tooth illustrating the benefit of virtual rotation; **(C)** Virtually extracted pulp with the enamel and dentine removed. Micro-CT images originates from the PhD thesis by the main author for which ethical clearance (reference number: 298/2020) was obtained.

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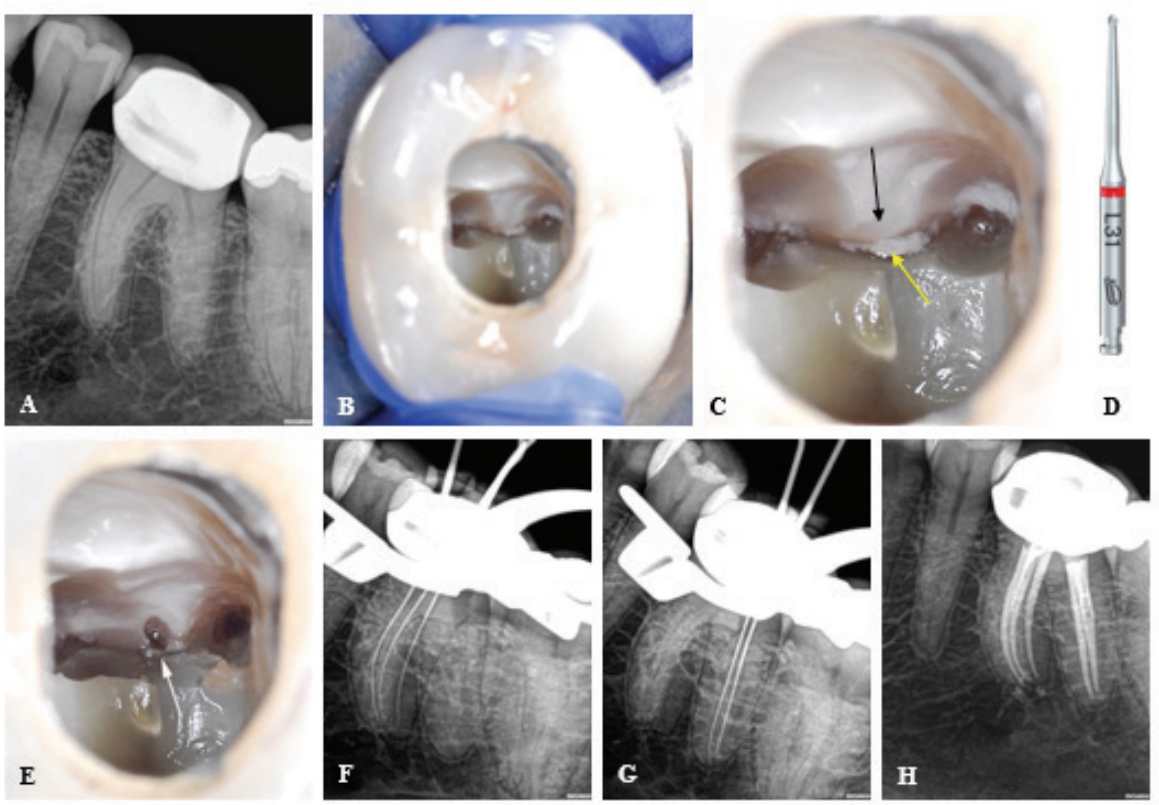

Figure 3: A clinical case presentation of a mandibular first molar with an MM canal; **(A)** Pre-operative periapical radiograph of a left mandibular first molar; **(B)** Access cavity preparation through the ceramo-metal crown; **(C)** High-magnification view of the mesial aspect of the pulp chamber. Note the dentine ledge (black arrow) and pulp tissue remnants (yellow arrow) in the groove connecting the MB and ML root canal orifices; **(D)** 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; **(E)** High-magnification view of the mesial aspect of the pulp chamber after removal of the dentine ledge exposing the orifice of the MM root canal system; **(F)** Periapical radiograph to determine the length of the three mesial root canal systems; **(G)** Periapical radiograph to determine the length of two distal root canal systems; **(H)** Postoperative periapical radiograph after obturation of the five located root canal systems. Note the three separate mesial canals (3-3-3 configuration in mesial root).

mandibular molars, namely the middle-mesial canal located between the mesio-buccal (MB) and mesio-lingual (ML) canals.[2,6] The incidence of this type of morphology has been a focus of investigations for years. Authors have reported on the prevalence in different populations ranging anywhere from 0%[24] in a Vietnamese population and as high as 59% in an Indian population.[25] The different percentages noted could reflect the methods of investigation: for example, in an unknown population in the US a prevalence of 11.5% was reported during clinical treatment;[26] a clearing technique in a Pakistani population revealed 3.3% prevalence;[27] 17.2% was reported using a dental operating microscope on extracted teeth in a Brazilian subpopulation;[28] 2.2% was reported in a Chinese population using CBCT;[10] and a clearing and staining technique was used on extracted Sri Lankan first molars and revealed a prevalence of 0.2% for an additional mesial canal.[29]

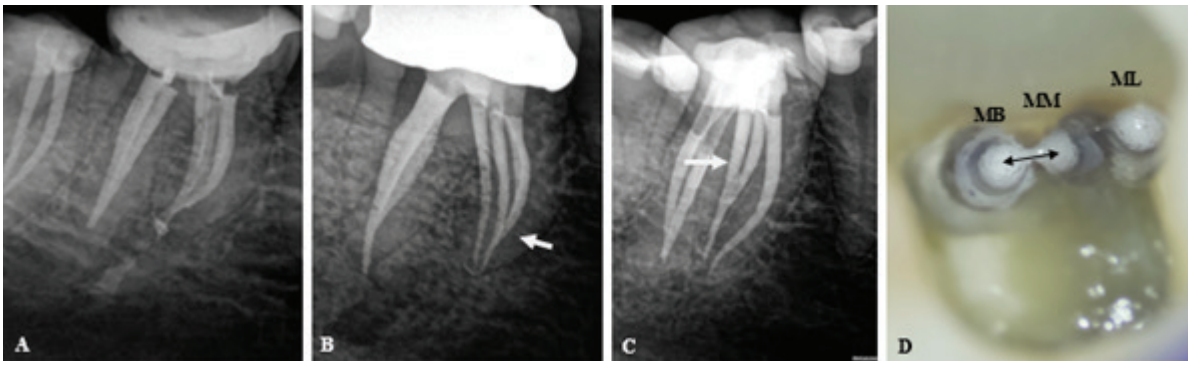

Figure 4: MM root canal configurations encountered during clinical management of mandibular first molars in South African individuals; **(A)** Postoperative periapical radiograph after obturation of five root canal systems in a right mandibular first molar. Note that the three separate mesial root canal systems join in the apical third of the root to exit in a combined apical foramen (3-3-1 configuration in mesial root); **(B)** Postoperative periapical radiograph after obturation of five root canal systems in a right mandibular first molar. Note that the MB and MM root canal systems join in the apical third of the root (white arrow) to exit in a combined apical foramen, while the ML canal system remains separate (3-3-2 configuration in mesial root); **(C)** Postoperative periapical radiograph after obturation of five root canal systems in a right mandibular first molar. Note that the ML and MM root canal systems join in the middle third of the root (white arrow) to exit in a combined apical foramen, while the MB canal system remains separate (3-2-2 configuration in mesial root); **(D)** High-magnification view of the mesial aspect of the pulp chamber of a left mandibular first molar. Three mesial root canal systems were located; the MB and MM orifices are very close together (arrow) and joined as one canal in the coronal third of the root.

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Table I: Micro-CT investigations in different populations including sample size and prevalence.

Author(s)	Year	Population	Number of teeth investigated	Prevalence of MM (%)
Gu *et al*.[38]	2010	China	122	0.8
Harris *et al*.[39]	2013	USA	22	36.4
Versiani *et al*.[6]	2016	Brazil	136	22.1
Versiani *et al*.[6]	2016	Turkey	122	14.8
Moe *et al*.[40]	2017	Burma	181	18.7
Marceliano-Alves *et al*.[41]	2019	Brazil	140	7.7

In a more recent global study, Hatipoglu *et al.*[30] invited 15 countries to participate in a CBCT study on the prevalence of the MM canal. Although CBCT devices did vary, this study reduced the possible variable of using different methodologies to identify the MM canal. Their findings were: Poland 1%, Germany 15%, Croatia 1%, Portugal 4%, Turkey 8%, Kazakhstan 5%, Pakistan 8%, India 10%, Malaysia 2%, Saudi Arabia 13%, Yemen 2%, Libya 23%, Jordan 2%, South Africa 2% and Egypt 1%.

Only a few authors have reported on the prevalence of the MM canal in African populations. In general the MM canal is either absent or has a low prevalence in African groups: no MM canal was found in Senegalese,[31] Ugandan[32] and Tanzanian[33] populations using a clearing and staining technique. In a Kenyan study a prevalence of 0.5% was reported,[34] 1% in an Egyptian using CBCT[30] and 20% in a CBCT study from South Africa.[35] Two African groups presenting with a higher prevalence were Arabs in Libya[30] (23%) and a mixed South African group[35] (20%).

Case reports describing the clinical management of this additional root canal are also available.[36,37] Figure 3 illustrates the clinical procedure to remove the dentine ledge and uncover the middle mesial canal system on a mandibular first molar. Figure 4 depicts more examples of MM canal configurations treated in South African individuals.

Micro-CT studies, which are expected to detect MM canals more accurately, are scarce. Although higher prevalences are reported using this technique than with other techniques, results vary even within one country (Table I). For example, in Brazilian micro-CT studies figures of 7.7% and 22.1% are reported. The demographics of the individuals in these studies are unclear, but it seems that extracted teeth from individuals from different regions, namely Rio de Janeiro and Sao Paulo, were used. There were also differences between scan resolutions.[6,41] Other authors mention that differences between resolutions in scans should also be considered when interpreting results.[14,19] No studies were found reporting on the presence of MM canals in African or South African populations using micro-CT.

The middle-distal canal (MD)

An additional canal can be present in the distal root outside the expected number of one or two. It is not clear whether the reported variance in prevalence of an MD canal can be attributed to different populations or the use of different techniques. Micro-CT seems to improve the detection of an additional canal and revealed the highest percentages: 11%[42] in first molars in a Brazilian population and even 22.5% in unspecified molars in an Egyptian sample.[43] The prevalence of additional distal canals in other global populations found using other techniques is: radiographic: 1.7% in India[44] and 0.6% in a Spanish population[45] (clearing and staining); 1.7% in Burma,[46] 1% in Turkey[16] and none in Uganda, Kenya and Tanzania[32-34] (CBCT); 0.5% in UAE[47] and none in Portuguese,[48] Brazilian[49,50] and Vietnamese groups.[24]

In Africa, a few studies were identified reporting on the presence of the MD canal. In Senegal individuals of African descent were investigated and a prevalence of 0.2% was noted by direct observation.[31] Clinical investigation in a Kuwaiti population revealed no teeth with additional distal canals.[51] In South Africa, a group of authors using CBCT

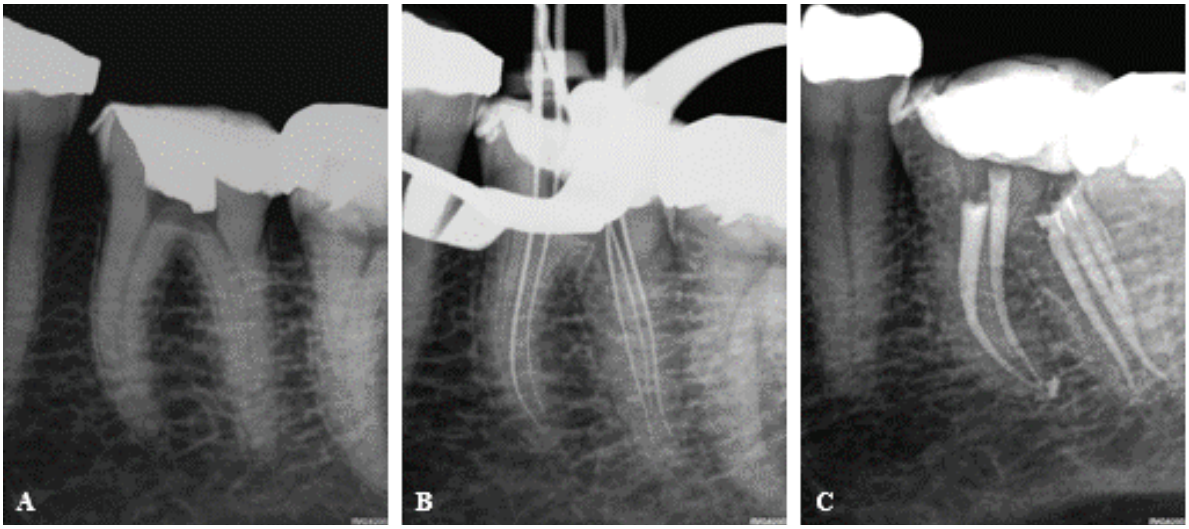

Figure 5: The clinical management of a mandibular first molar with an MD canal; **(A)** Pre-operative periapical radiograph of a left mandibular first molar; **(B)** Length determination periapical radiograph. Note the three distal root canal systems in the distal root; **(C)** Postoperative periapical radiograph after obturation of the five root canal systems. Note that the MD and MB canals join in the apical third of the root while the distolingual canal is separate (3-3-2 configuration in distal root).

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reported a 7.3% prevalence of more than the expected one or two canals.[35] It is not known why a greater prevalence was noted in this study compared to others using CBCT. Resolution of the CBCT scans could be different or techniques and experience could vary.[14,52] In the US, using micro-CT Harris *et al*.[39] found a single tooth that contained a three-canalled configuration, giving a prevalence of 4.5% from 22 teeth. As with the MM canals, no studies that focused on African or South African populations using micro-CT were found. A number of case reports describe the clinical management of additional distal canals.[53,54] Figure 5 shows a clinical example of a case with a middle distal canal in the distal root of a mandibular first molar.

Variants in canal numbers

Apart from the norm of three or four canals, cases have been reported of unusual internal canal morphology. Most are accidental findings and because of the rarity of the morphology they are published as case reports. These morphologies can range between one and 11 canals in a single tooth (Table II):

Table II: Case reports on variants in the number of total root canals.

Author(s)	Year	Number of canals
Reeh[55]	1998	7
Ryan *et al*.[56]	2011	6
Nagaveni *et al*.[57]	2015	1
Arora *et al*.[58]	2015	8
Chandra *et al*.[59]	2017	11

Figure 6 illustrates a clinical example and management of a mandibular first molar that presented with six root canal systems. Three canals were identified in the mesial root and three in the distal root.

Accessory canals

Ahmed and co-workers[60] describe an accessory canal as 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. The description includes what were previously known as lateral canals.[61] As long ago as 1984, Vertucci,[15] one of the first to report on root canal morphology, used a clearing and staining technique to report on accessory canals in different teeth. He determined that the mesial root of the mandibular first molar contained the highest number of accessory canals, and the apical region was the most likely area to find them. These findings were repeated in more recent micro-CT studies of various populations (Chinese, Brazilian and German).[38,41,62-65] Other studies report the presence of accessory canals in both roots using a clearing and staining technique[16] in a Turkish population and using micro-CT[39] on a US population. On the extracted Turkish first molars, sex variations were noted in the number per region of the root.[16] On the other hand, Gu *et al.*[38] report that in cases where an additional root is present, accessory canals are less common than in the main mesial and distal root canals. In both an American and a Ugandan sample, multiple portals of exit from accessory canals were noted.[32,39]

Although prevalence of accessory canals between populations varies (Uganda: 2.7% and China: 10% of molars studied) it is not clear if differences in methodology (clearing technique versus micro-CT) contributed to the difference noted. No studies could be found reporting on accessory canals in African or South African populations using micro-CT, but Figure 7 depicts the management of a clinical case in a South African individual where an accessory canal was present in the distal root. The figure also contains a micro-CT image of an extracted first molar from a South African individual with multiple accessory canals.

Chamber canals

Chamber canals may provide portals of communication between the periodontium in the furcation region and the root canal system.[66] Early reports include one from Vertucci,[2] who states that mandibular teeth have a higher prevalence of chamber communication with the furcation region than maxillary teeth (56% and 48% respectively). Other authors also report that patent chamber canals can be present in 29.4% of mandibular molars.[67] In a study from Turkey using a sectioning technique, 24% of mandibular first molars had patent chamber canals.[68] In a micro-CT investigation of German and Egyptian extracted teeth, a combined prevalence of 14.4% was reported.[66]

The prevalence of patent or inter-radicular chamber canals has been reported as 1.8%,[62] 4.2%[66] and 7.7%,[69] while 9.4%[69] and 10.2%[66] were blind-ended.[69] No studies reporting on the prevalence of chamber canals in African or South African populations using micro-CT could be found.

Apical deltas

Ahmed *et al*.[60] describe an apical delta or an apical ramification as a root canal network at or near the root apex where the main root canal divides into more than two

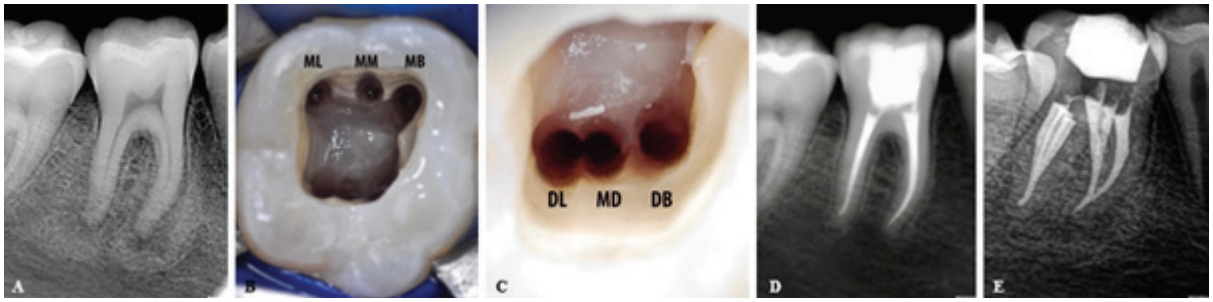

Figure 6: The clinical management of a mandibular first molar with an MM and MD canal; **(A)** Pre-operative periapical radiograph of a non-vital right mandibular first molar that presented with periapical pathology around the mesial and distal roots; **(B)** Magnified view of the pulp chamber showing the MB, MM and ML canal orifices after canal preparation with ProTaper Universal instruments (Dentsply Sirona); **(C)** High-magnification view of the distal aspect of the pulp chamber showing the DL, MD and DB canal orifices after canal preparation; **(D)** Postoperative periapical radiograph of the obturated canal systems; **(E)** Mesial angulated postoperative periapical radiograph showing the six obturated root canal systems (3-2-1 configuration in mesial root and 3-1-1 in distal root).

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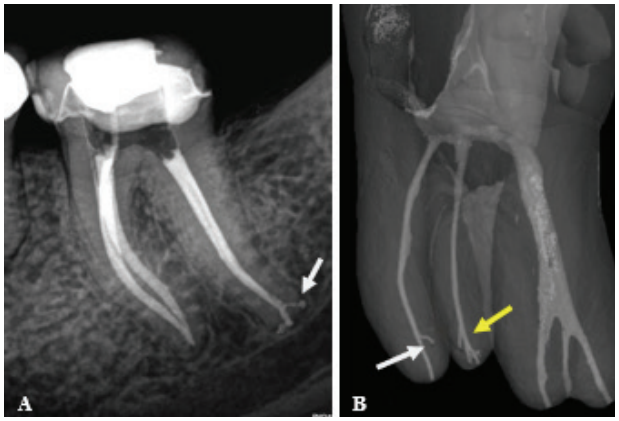

Figure 7: A clinical case and a micro-CT illustration of accessory canals located in the apical region of mandibular first molars; **(A)** Periapical radiograph of a left mandibular first molar that presents with an accessory canal (arrow) branching off from the main root canal system approximately 2mm from the root apex in the distal root; **(B)** Micro-CT image of an extracted first mandibular molar with complex anatomy. The MB root canal system has a blind-ending accessory canal (white arrow) in the apical third and the ML canal terminates into an apical delta (yellow arrow) (Image courtesy of Prof M Vorster).

accessory canals. Distribution of apical ramifications varies between populations, sexes, roots and methodologies used for detection. For instance, a Tanzanian study using a clearing and staining technique reported an absence of apical deltas;[33] a Brazilian micro-CT study found a prevalence between 2% and 12% for each root[65] and 16.5% of teeth (no distinction between first and second molars) in a Chinese population;[70] and in two micro-CT studies much higher percentages were seen – 80% in a Burmese[40] and 100% in a Chinese population.[38]

Apical deltas may be present in both the mesial and distal roots.[16] The literature reviewed did not agree on the predilection of either root. Some researchers report more deltas in the mesial root than in the distal:[70] for instance Vertucci reports an incidence of 10% for the mesial root and 14% for the distal root,[2] while other researchers report more in the distal root of the two-rooted group[38,62] and the main distal root of the three-rooted ones.[38] In a Turkish population the number of deltas was higher in males (19%-22%) than females (6%). In males more deltas were present in the distal root than in the mesial one, but in females the number of deltas was equal for the two roots.[16] No studies reporting on apical deltas using micro-CT in a South African population were found, but Figure 8 depicts a clinical case and management of a mandibular first molar that contained an apical delta. Figure 8 includes a micro-CT image of an extracted first molar tooth with an apical delta in a South African individual.

Root canal configurations

Root canal configurations provide insight into the complexity of the internal root and canal morphology of teeth.[71] To date, authors have used a variety of classification systems to describe common patterns and variants in mandibular first molars. The Vertucci system, which contains eight configuration types, is used by many as the gold standard for calculating a variety of teeth and methodologies including the mandibular first molar.[15,35,72-74] Vertucci[15] found that most American individuals studied contained type II (two canals joining at the apex) and type IV (two canals from orifice to apex) in the mesial root and type I in the distal (one canal from orifice to apex). Similar findings were reported in a micro-CT investigation on the mesial roots of Brazilian individuals.[75] In contrast, other findings are quite diverse.

For instance Salli and Egil,[74] using micro-CT, found more type III configurations (single canal dividing into two and joining again into one exit) in the mesial roots of Turkish individuals and Marceliano-Alves *et al*.[41] found more type IV configurations in the same root. In African studies, Rwenyonyi *et al*.[32] calculated more type IV configurations in the mesial root and only type I in the distal root of Ugandans; Madjapa and Minja[33] calculated more type II in the mesial and type I in the distal roots (n=146) of Tanzanians; Muriithi *et al*.[34] found predominantly type IV in the mesial root and type I in the distal (n=189) of Kenyans; and Sperber and Moreau[31] calculated more type III in the mesial root and only type I in the distal of Senegalese individuals. In South Africa, Tredoux *et al*.[35] used the Vertucci classification system with additions from Sert and Bayirli.[16] They found several configurations distributed between[23] configuration types, but type IV in the mesial roots and type I in the distal were more prominent (n=371).

Recently the Ahmed classification system has been accepted in morphological studies.[76] In this system, classifications are made by considering the orifice, canal(s) pathway and foramen (O-C-F) and can include complexities (Figure 9).

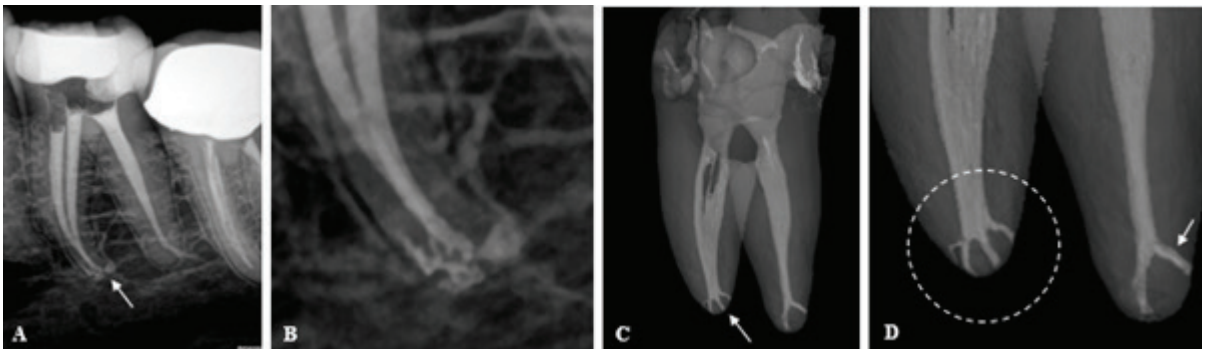

Figure 8: A clinical case and micro-CT images of an extracted tooth illustrating the presence of apical deltas; (A) Periapical radiograph of a left mandibular first molar that presented with one distal and two mesial root canal systems that joined in the apical third ending in an apical delta (arrow); **(B)** Magnified view of the apex of the mesial root of the same tooth showing the apical delta; **(C)** Micro-CT image of an extracted first mandibular molar. Note the MB, MM and ML root canal systems that join in the midroot area into one canal and then terminate at the root apex into an apical delta with four portals of exit. The distal root canal system has a single patent accessory canal branching from the main canal in the apical third of the root; **(D)** Magnified view of the apices of the mesial and distal roots. Note the combined mesial canals that exit as a delta (circle) and the accessory canal that branches off from the main distal canal system (arrow) (Image courtesy of Prof M Vorster).

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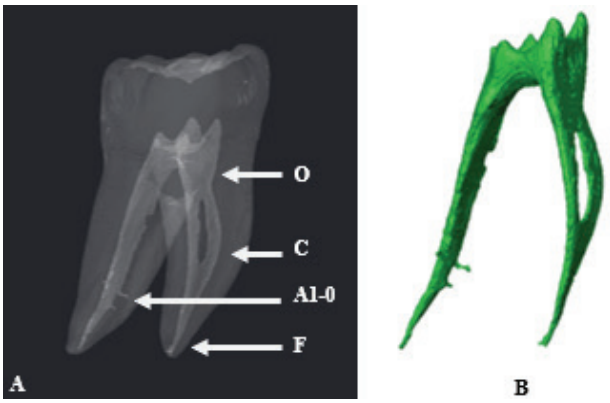

Figure 9: A summary of the root canal configuration calculation according to criteria of Ahmed et al.;[60,76] **(A)** Root canal configuration of a mandibular first molar to include main and accessory root canals. In this example, there is one orifice in both the mesial and distal root canal systems (O). In the mesial system, the canal divides into two and joins again into one. In the distal there is only one canal with no divisions (C). In both the mesial and distal systems there is one main foramen at the apex (F). In the distal system there are blind-ended accessory canals in the apical third (A1-0). The configuration for this tooth is therefore ^{2}MFM M$^{1\text{-}2\text{-}1}$D$^{1(2A1\text{-}0)}$ indicating a two-rooted mandibular first molar with its internal root canal morphology; **(B)** Extracted pulp from the same tooth displaying the internal canal morphology. Micro-CT images originate from the PhD thesis mentioned earlier.

Most studies using the Ahmed classification system used CBCT as the investigative method.[72,73,77-79] However, studies applying this new classification system in mandibular first molars are scarce. Using CBCT, Abarca *et al*.[77] determined that most molars had a ^{2}MM M$^{2\text{-}1}$ D^{1} configuration; in other words, in this configuration there are two orifices, two canal pathways and one apical foramen in the mesial root and a single canal from orifice to apical foramen in the distal root. To the best of the authors' knowledge, no micro-CT studies using the Ahmed system to calculate root canal configurations to include complexities (for example accessory canals and deltas) are available.

DISCUSSION

The root canal morphology of the mandibular first molar is highly diverse and can differ greatly among populations and even individuals within populations. Genetic factors could account for the variations noted in the anatomy of molars between ethnic groups and those from different geographical areas, but external factors could also contribute.[72,79,80] These differences are not just interesting but could play an important role in treatment approaches and, ultimately, successful treatment outcomes. In cases where root canals remain undiscovered or where additional roots are undiagnosed, it is very likely that treatments will fail. Hidden morphology can harbour infected or irreversibly inflamed tissues.[2,81]

The findings on various populations are invaluable as they provide insight into the anticipated root and canal morphology within each population. In the literature reviewed, the prevalence of three canals for mandibular first molars ranges between 42.2%[82] and 89.4%[83] and between 6.6%[83] and 57.8%[82] for four canals: two in the mesial root and one or two canals in the distal root.[2,7,84]

Using CBCT, an additional root has been reported in up to 59%[25] of some populations but is absent in others.[24] Locally, two CBCT studies report incidences of 5.2% and 1% respectively for additional roots in a mixed group of South Africans.[14,35] As a mixed group was used it is not known what the prevalence in individual populations is. Interestingly, in studies on several African populations where clearing and staining were used, no teeth were identified containing an MM canal (Senegal, Uganda and Tanzania) or very few (0.5% in a Kenyan study).[31-34] The cause of this low prevalence of the MM canal, whether it stems from inherent characteristics of the population or the clearing technique employed, remains uncertain.

Study design and methodology, including sample sizes, could cause the variations noted in the internal root and canal morphology of the mandibular first molar. Investigators have used a variety of methods to study root and canal morphologies of mandibular first molars. In the past, clearing and staining was the method of choice and was advocated by some of the most influential researchers of their time.[13,15] However, this technique has limitations that could have affected the discovery of hidden anatomy.[85] Other techniques are radiography,[17] Scanning Electron Microscopy (SEM)[31] and magnification.[86] In recent years, morphological studies have been dominated by 3D techniques such as CBCT and micro-CT.[18] Although CBCT has a clinical application benefit and micro-CT cannot currently be used on live patients, micro-CT is now the modality of choice for investigating complex internal root morphology, as it can identify very fine detail of the pulpal complex that is easily missed using other techniques.[18,76,87]

A very important discovery was made in a micro-CT study that found that 7.5% of MM canals were 2mm or more inferior than the cemento-enamel junction.[88] The clinical dilemma is that the orifices of MM canals are often covered by dentine, which must be removed with burs to uncover and gain entrance to them. Removing additional tooth structure can increase the risk of perforation and proper magnification is paramount.[89,90]

The MD canal is another example of how micro-CT improves the visualisation of root canal morphology. Global prevalence of the MD canal varies from 0%[48] in a CBCT study to 11% in a micro-CT study.[42] It is also interesting to note that the same authors who reported no teeth containing an MM canal in African populations (Uganda, Senegal, Tanzania and Kenya) also found no additional canals in the distal root when using a clearing technique. Using CBCT, more than two canals were noted in 7.3% of South Africans while in a Brazilian micro-CT study this was 11%.[31-35,42] Finally, sometimes these teeth can have either one, six, seven, eight or even 11 canals in total (Table II). These findings appear to be quite rare and reports are available where they have been treated.[58,59] Clinicians should also be mindful of the presence of additional canals in the distal root and, although the incidence is lower than for MM canals, it is easy to assume that when one or two canals are discovered a complete diagnosis has been reached. There must be a proper diagnostic protocol and a treatment strategy to deal with any number of canals that can be present. Additional canals should be assumed to be present until proven otherwise.

It is important to consider accessory canals, chamber canals and deltas during endodontic treatment. These root canal morphologies are relatively common and often create a pathway between the pulpal space and the outside of the

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root (the periodontal ligament space). Accessory pathways encapsulate blood vessels during the development of a root and exist as interrupted areas of development of the Hertwig root sheet.[64] These canals are often out of reach of root canal instruments and isolated from the flow of irrigation solutions. This could be problematic, as causative organisms and their by-products can move from infected root canals to the periodontal ligament creating periodontal disease or the pulp can be infected when periodontal disease is present.[91] Clinicians should always be mindful of this and follow a strict mechanical and chemical approach for optimal cleaning, shaping, disinfection and eventual 3D obturation of the prepared spaces.

There is consensus that the mesial root contains the most accessory canals, mainly in the apical third,[15,16,38,39,41,63-65,92] although both roots can contain them even where additional roots are present.[16,38] It has also been reported that the apical 3mm of roots contain the most accessory canals. This finding is important to consider in cases where apical surgery is required to remove at least 3mm of the root apex.[39,93] The presence of accessory canals in the apical 3mm may be linked to the high prevalence of biofilms of organisms in the apical part of root canals of teeth diagnosed with apical periodontitis.[91]

There is another type of accessory canal that could create a communication channel between the pulp space and the furcation region, namely the chamber canal. If patients suffer from periodontal disease, a seemingly healthy tooth can become infected through these channels.[94] The prevalence can be as high as 29.4%[67] for mandibular first molars. Clinicians should be mindful of the potential risk of contamination when a tooth is obturated and restored. Chamber canals have been observed using radiographs,[95] clearing and dyes[69] and SEM.[96] A few micro-CT investigations are also available. The first micro-CT study was conducted in 2022 using Egyptian and German extracted teeth.[66] The chamber canals were described as patent (inter-radicular) or blind-ending (diverticulum) which is similar to terminology suggested by Ahmed *et al*.[22,60,76] Any form of chamber canal can contain organic tissues that can ignite an inflammatory response.[66]

The presence of apical deltas is also an important morphological component of root canals. They provide the main root canal with multiple portals of communication with the outer surface of the root at the apex. To qualify as a delta according to Ahmed *et al.*,[60] the main canal must divide into multiple smaller branches and contain more than two accessory canals.[22,60,76] It does seem that the distal root may contain more apical deltas than the mesial root, as high as 16%. Micro-CT studies focusing on apical deltas are not common but a Chinese study reported that apical deltas are more common in the distal roots of two and three-rooted first molars but less common in the additional roots.[38]

Root canal configurations can play an important role during the diagnostic and treatment planning phase of endodontics. Over the years several classification systems have been suggested. One of the earliest is that of Weine *et al*.,[97] which laid the platform for future developments but contained only three configuration types. Since then, systems have evolved to include more complex configurations.[15,16,21,46,63,98-101] Unfortunately, shortcomings have been noted, especially the inability to include detail.[71]

The introduction of the Ahmed *et al*. system made it possible to include fine detail in calculations, such as accessory canals, apical deltas, complex connections and many other morphological findings.[60,76] The Ahmed *et al*. classification is accepted by the research community and has clinical and academic applicability to undergraduate and postgraduate training.[102,103] Despite its numerous advantages and although the inclusion of fine detail could be beneficial, it can add to the complexity of classification and create confusion for researchers and a degree of subjectivity,[76] which can make it difficult to compare findings.[18]

No micro-CT studies were found that described configurations including accessory canals, chamber accessory canals or apical deltas on any tooth using the Ahmed *et al*. classification system. It seems that current challenges lie in developing a classification system that accommodates micro-CT and includes as much detail as possible without increasing complexity, though such a system would have to be universally accepted. A classification system or modification using the criteria of Ahmed *et al*. to include fine detail in an understandable and repeatable way could be beneficial for researchers. It might provide an additional advantage in the ability to compare the complexity of various teeth in different populations, although standardised landmarks and descriptions will be required for calculation purposes.

In conclusion, the root canal morphology of the mandibular first molar is complex and varies according to population. Clinicians should be mindful of possible additional root canals and accessory root canal anatomy that may include MM and MD canals, accessory canals, chamber canals and apical deltas. Currently, there is a shortage of research on African and South African populations using micro-CT.

Declaration

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Conflict of interest

We declare that there is no conflict of interest.

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Online CPD in 6 Easy Steps

The Continuing Professional Development (CPD) section provides for twenty general questions and five ethics questions. The section provides members with a valuable source of CPD points whilst also achieving the objective of CPD, to assure continuing education. The importance of continuing professional development should not be underestimated, it is a career-long obligation for practicing professionals.