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First permanent molar root canal configurations in a South African sample: a descriptive micro-computed tomographic report

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ABSTRACT

The aim of this paper was to describe root canal configurations using micro-CT in South African first molars. A segmentation process was followed on micro-focus X-ray computed tomography (micro-CT) scans of 101 maxillary and 86 mandibular first molars. Main and accessory root canal anatomy were considered to describe root canal configurations. Intra- and inter-observer reliability was determined using the unweighted Cohen's Kappa test. Intra- and inter-rater agreement was 93% for maxillary configurations; 92.9% and 86.2% respectively for mandibular configurations. The most common main canal configurations were: $^{3}M_{X}FM\ MB^{1}DB^{1}P^{1}$ (n = 33/93, 35.5%) and $^{2}M^{D}FM\ M^{1\text{-}2}D^{1}$ (n = 8/84, 9.5%) (separate three-rooted maxillary and two-rooted mandibular respectively). The addition of accessory canals resulted in configurations that were mostly individualised with only a few notable similarities. A total of 97 unique configurations were found in maxillary teeth and 85 in mandibular teeth. In the separate three-rooted maxillary molars, the only similarities were $^{3}M_{X}FM\ MB^{1(A2)}DB^{1(A1)}P^{1}$ (n = 4/93, 4.3%) and $^{3}M_{X}FM\ MB^{1(A1)}DB^{1(A1)}P^{1}$ (n = 2/93, 2.2%). In two-rooted mandibular molars, only $^{2}M_{D}FM\ M^{1}D^{1}$ (n = 2/84, 2.4%) was noted. Root canal configurations were found to be diverse and complex.

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Keywords
Accessory canals, first molars, micro-CT, root canal configurations

Introduction

The basis of successful endodontic treatment outcomes is a sound knowledge of root and canal morphology.[1] Failure to identify and disinfect all areas of a root canal system may result in treatment failure.[2] The root canal configurations in first molars have been shown to be complex with differences between sex, populations and variations between geographic distributions.[3-6]

With the advent of new imaging modalities, a clearer understanding of the root canal system has now been discerned. While cone-beam computed tomography (CBCT) is advantageous for its clinical applications and investigation of root and canal morphology, it is difficult to identify complex root canal morphology and accessory canals unless they are large enough to be visualised.[7] Because of its high resolution, micro-focus X-ray computed tomography (micro-CT) has been suggested and confirmed as the most appropriate modality to focus on fine detail, often not detected or visible using other investigative methods.[8,9]

Root canal configurations can form an integrated component of treatment planning and execution during retreatments or planned apical surgery.[10] To allow some degree of predictability, investigators attempted to identify common

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configurations using a classification systems. Recently, Ahmed and co-authors suggested a classification system along with guidelines and terminology for CBCT and micro-CT scans.[7,11,12] This system made provision for the inclusion of complex root and canal morphologies in a clear and understandable manner.[12,13] The system has gained popularity from researchers and undergraduate teaching institutions worldwide.[11,14] As researchers and clinicians, it is important to consider all relevant root and canal morphology.[1] To date, the research available on the mandibular first molars of South Africans is limited, with most authors using CBCT on mixed or undisclosed populations.[15-18] One South African CBCT study, using the Vertucci classification system with modifications from Sert and Bayirli[19] reported that configurations were diverse, but accessory canals or other canal complexities were not considered.[20] The objectives of this study are to report on root canal configurations of maxillary and mandibular first permanent molars using the Ahmed *et al.* classification system and micro-CT technology.

Materials and Methods

Ethical approval was obtained from the Research Ethics Committee of the Faculty of Health Sciences, University of Pretoria (Protocol number: 298/2020). The study design was quantitative, descriptive, cross-sectional and observational and reporting followed the Strengthening the Reporting of Observational studies in Epidemiology (STROBE) guidelines[21] (Figure1).

The methodology of this project was based on previous work by Jonker *et al.*[18,22] Additionally, the configurations in fused roots was further described as follows: separate root canal (/) or shared root canals (//). For describing configurations, maxillary first molars were allocated the code M_XFM and mandibular first molars M_DFM to avoid confusion between teeth from different arches. All scans were anonymously analysed with no prior knowledge of arch side, age or sex of the sample.

Origin of scans

Human skulls with known age, sex and population affinity were sourced from the Human Osteological Research Collection (HORC) housed in the Anatomy and Histology Department of the Sefako Makgatho Health Sciences University (Pretoria, South Africa) and the Pretoria Bone Collection (PBC) housed in the Department of Anatomy of the University of Pretoria (South Africa).[23] Permission for research was provided by family members of deceased individuals and ultimately these bodies form part of the whole body donation programme. In cases of third-party donations, the Director General, in conjunction with the Health Officer, provided authorization for research purposes. The use of all bodies in research and education is stipulated in the National Health Act 61 of 2003 (amended in 2013).

Scanning of skulls took place at the South African Nuclear Energy Corporation (Necsa, Pelindaba, South Africa) using the Nikon XTH 225L industrial CT system (Nikon Metrology, Leuven, Belgium) micro-focus X-Ray computed tomography scanner and the following settings: 100 kV voltage, 100 mA current and 2.00 seconds exposition time per projection, x-ray unit with a spot size ranging between 0.001 and 0.003 mm (1 - 3 µm), a rotation accuracy to 1/1000th of a degree of the translation table and a pixel size of 200 µm x 200 µm. The Perkin Elmer detector of the unit has a 400 mm x 400 mm field of view; an estimated 200 mm x 200 mm field of view was used to scan each maxilla or mandibulae.[24] After completion of scanning, two-dimensional projection images were reconstructed with the Nikon CT Pro version 4.4.3 software (Nikon Metrology) into 3D volumes. Isotropic voxel size/scan resolutions ranged between 40.3 µm and 74.2 µm. The final step involved the importation of the final 3D volumes into Avizo 2019 3D visualization software (Thermo Fisher Scientific Inc.) for the subsequent post-acquisition processes.[25]

Segmentation, alignment and image acquisition

Using the Isosurface module of the Avizo 2019 software, each micro-CT scan was rendered in 3D. Each maxillary first molar was virtually extracted by cropping and segmenting each scan. The cemento-enamel junction (CEJ) was used as a readily identifiable reference for the placement of landmarks on each tooth.[26] For both maxillary and mandibular molars, landmarks were placed at the highest occlusal point of the CEJ for each root on the buccal and palatal or lingual surfaces.

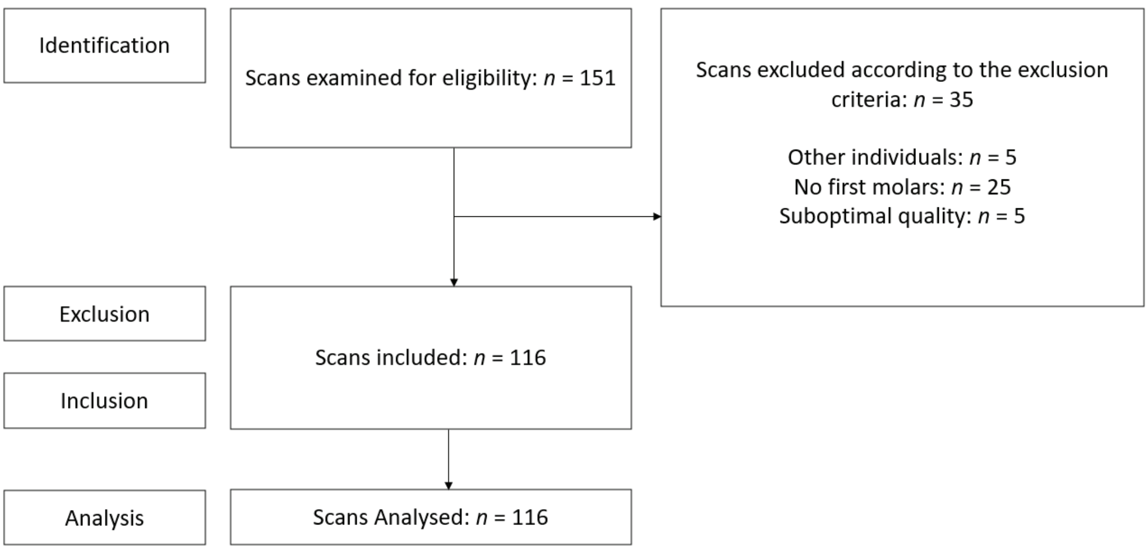

Figure 1: STROBE flow diagram to determine eligibility of available scans.

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The Avizo 2019 software can automatically compute a best-fit plane at the level of the CEJ based on these landmarks, which was used as a reference to re-align the micro-CT image stacks. The introduction of oblique sections and possible bias was reduced by repeating the same steps for each scan. The image brightness, contrast and sharpness parameters were then adjusted within Avizo for optimal visualization. The same settings were duplicated for each scan to ensure standardization.

By using the watershed method (region-based semi-automatic segmentation procedure), a virtual extraction and 3D observation of the root canal network was made possible.[27] Segmentation is a process in which each tooth and its inner components (enamel, dentine and pulp) are virtually isolated from each other. Different colours were allocated to each tooth component to allow differentiation between components. A masking or multiple slice edit procedure[28] was followed to carefully edit and correct slices where teeth had dentinal cracks in communication with the pulpal space or exterior spaces beyond the roots.

Scan analysis

Scan analysis and data capturing followed a similar methodology as previously described by Jonker *et al.*[22] Unique codes were allocated to each scan and data capturing was completed anonymously. For each scan, the pulps were isolated, magnified and rotated accordingly using the settings and parameters within Avizo. The same process was followed for each scan. Configurations of teeth with fused roots were described following the Ahmed *et al.*[7,29] and Zhang *et al.*[30] criteria. Teeth with C-shaped canals were described according to the Fan *et al.*[31] criteria and the presence of the radix entomolaris (RE) according to the criteria stipulated by Song *et al.*[32] Root canal bifurcations were identified based on descriptors and illustrations by Xu *et al.*[33]

The root canal configurations of all teeth in the sample were firstly calculated and recorded by the main researcher, an experienced operator in the field of endodontics and micro-CT. The guidelines and terminology as described by Ahmed *et al.*[7,12,13] were followed. The following figures (Figures 2 and 3) provide a summarised, descriptive illustration of the nomenclature of the Ahmed *et al.* system for root canal pathways, accessory canals, chamber canals and apical deltas used in this project.

A second researcher, a specialist and consultant in prosthodontics with experience in endodontics, participated in an inter-observer reliability test. Prior to the test, both researchers were calibrated. This calibration consisted of a consensus opinion of the guidelines and criteria of the Ahmed *et al.* classification system by evaluating two

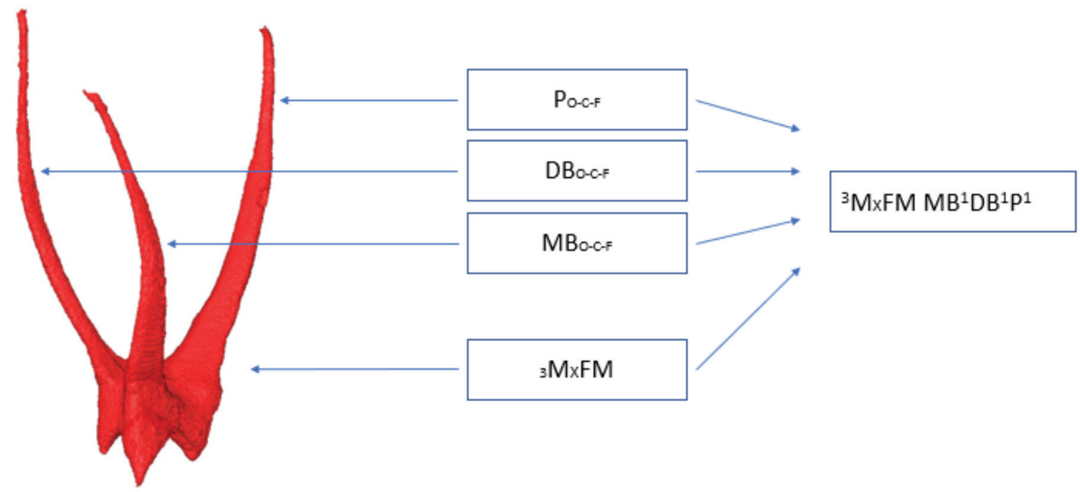

Figure 2: Three-dimensional model of the pulp extracted from a three-rooted maxillary first molar from the current study, with one root canal in each of the mesiobuccal (MB), distobuccal (DB), and palatal (P) roots. A single code is used to describe the number of roots as indicated by a superscript at the front or left of the configuration. To the right of tooth number or code, the letters O (orifice), C (canal) and F (foramen) are used for each root configuration as shown above.

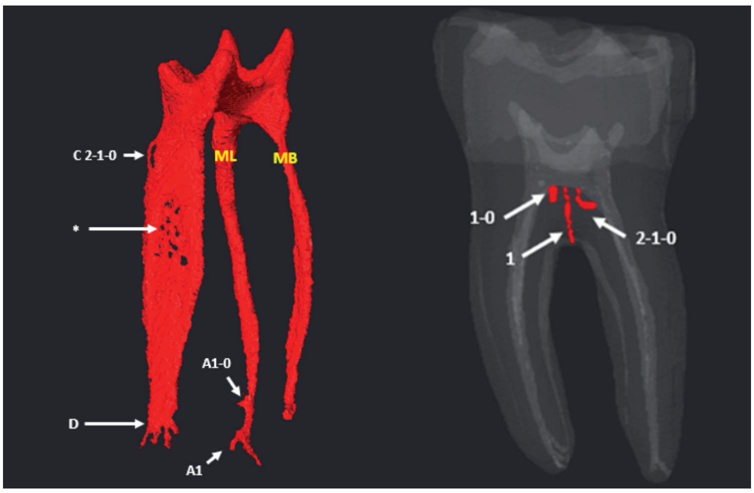

Figure 3: Classification of accessory canals and chamber accessory canals according to Ahmed *et al.* [12, 13] Left: 3D model of a mandibular first molar with C (2-1-0), a looped accessory canal in the coronal third of the distal canal; A (1-0), a blind-ended accessory canal in the apical third of the mesiolingual (ML) canal; and A (1), a patent accessory canal in the apical third of the ML canal. No accessory canals are present in the mesiobuccal (MB) canal. * indicates the presence of complex mesh-like connections in the coronal to midroot area of the distal root canals. Right: 3D model of a mandibular first molar in semi-transparency and showing examples of chamber accessory canals marked in red which have been added to the image for illustrative purposes: looped (2-1-0), blind-ended (1-0) and patent (1).

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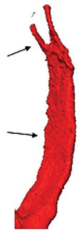
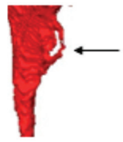
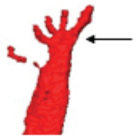
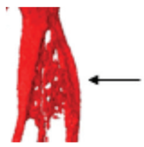
The terminology that was developed and used for this study is summarized in the glossary of terms (Table I).

Table I: Glossary of terms.

Root canal bifurcation	Divisions of the original main canal into two separate branches where the terminating branches have similar size and diameter	
Two canals with isthmus from coronal to apical	Two joined canals that appear like a single ribbon-shaped/flat canal but a root canal bifurcation is present at the apical third	
Blind accessory canal	Rod, spike, or fan-shaped root canal branches extending markedly from the main canal and follow an interrupted pathway enroute to the exit on the external root surface	
Loop accessory canal	Semi-lunar root canal located on the lateral aspect of the main canal, with a relatively smaller diameter where both ends are connected to the main canal	
Patent accessory canal (excluding chamber canals)	Root canal branches located in either the coronal, midroot or apical region that deviates from the main canal in any direction exiting on the external root surface	
Apical delta (apical ramifications)	Division of the main canal into multiple accessory canals (more than 2) and where all the accessory canals are located in the apical third independent of their distance from the apex	
Complex root canal connections (*)	Root canals that are connected by multiple intercanal communications resulting in a multi-digit Ahmed *et al.* configuration (more than 6 digits) or a mesh-like network of intercanal communications	

randomly chosen scans unrelated to the main test. During the main reliability test, the two researchers completed calculations of configurations independently and results were compared. Configurations were accepted in the event of agreement and any discrepancies in results were discussed until consensus was reached. Inter- and intra-rater reliability were determined

Inclusion criteria

The highest possible resolution scans (no blurring or double images) of self-identified South Africans of African descent with intact roots and fully developed apices, where the pulpal space could be accurately isolated were included.

Exclusion criteria

Teeth with incomplete root formation, root fractures, coronal or radicular resorption, existing root canal treatments, extensive decay obstructing any root canals, metallic restorations, scans of suboptimal quality and other self-identified population groups were excluded.

Sample size

A convenience sampling method was used from available maxillary and mandibular scans (n = 151) to limit selection bias. After consideration of the inclusion and exclusion criteria, the final selection of teeth included 101 maxillary and 86 mandibular first molars from a total of 116 scans from

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87 individuals (48 males and 39 females). Slightly more teeth from the right side (53 maxillary and 44 mandibular molars) than the left (48 maxillary and 42 mandibular molars) was identified. More males (50 maxillary and 48 mandibular) than females (51 maxillary and 38 mandibular) were included in the sample. Ages ranged between 20 and 89 years.

Statistical analysis

Statistical analysis was performed with R Statistical Software version 4.1.1 (R Core Team 2021, Vienna, Austria). For all tests, a significance level of 5% ($p < 0.05$) was selected. Intra- and inter-observer reliability and agreement were assessed using a randomly selected sample of approximately 20% of the total sample size (n = 37/187, including 20 maxillary and 17 mandibular molars). Percentages of agreement were determined using unweighted Cohen's Kappa tests.

Results

Sample characteristics and examiner agreement

The intra-rater analysis between the two rounds of calculations for the maxillary molars revealed a 93% agreement, which was confirmed by unweighted Cohen's Kappa ($k = 0.93$, $z = 8.14$, $p < 0.001$). For mandibular molars, a 92.9% agreement between rounds was achieved ($k = 0.929$, $z = 9.27$, $p < 0.001$) according to unweighted Cohen's Kappa. Regarding the inter-observer reliability for the maxillary molars, a 93% agreement was achieved between raters confirmed by unweighted Cohen's Kappa ($k = 0.93$, $z = 8.14$, $p < 0.001$). For the mandibular molars, an 86.2% agreement was achieved between raters using unweighted Cohen's Kappa ($k = 0.862$, $z = 7.91$, $p < 0.001$).

Main root canal configurations according to the Ahmed *et al.* classification.

Maxillary first molars with separate roots

Findings are summarized in Table II. Ninety-three maxillary first molars with separate roots showed a total of 33 different configurations. The most common configuration was $^{3}M_{X}$FM MB^{1}DB^{1}P^{1} (n = 33/93, 35.5%) indicating that a single canal is present in each of the three roots with a single orifice, pathway, and apical exit (O-C-F). The next most common configurations were $^{3}M_{X}$FM MB$^{1\text{-}*\text{-}2}$DB^{1}P^{1} (n = 7/93, 7.5%), $^{3}M_{X}$FM MB$^{1\text{-}2}$DB^{1}P^{1} (n = 7/93, 7.5%) and $^{3}M_{X}$FM MB$^{1\text{-}2\text{-}1}$DB^{1}P^{1} (n = 6/93, 6.5%). A total of 22 individualized configurations were present, each representing 1.1% of the three-rooted sample (n = 1/93; 1.1%). A single tooth was identified with taurodontic traits (n = 1/93; 1.1%).

Maxillary first molars with fused roots

Findings are summarized in Table III. Eight maxillary first molars were observed where roots displayed fusion, with a total of eight different configurations, i.e., no notable patterns were identified. In five of the teeth with fused roots, the root canals were joined (//) and shared between roots (n = 5/8; 62.5%). The most common type of root fusion was type 3 (n = 5/8, 62.5%) including one tooth with an enamel pearl (EP) (n = 1/8; 12.5%). In two teeth, a type 1 fusion with joined root canals were noted, including one with a

Table II: Root canal configurations of separate three-rooted maxillary first molars according to Ahmed *et al.* excluding accessory canals, deltas, or pulp chamber canals (main canals only).

Configuration	Number of teeth	Cumulative total (number of teeth)	Total percentage (%)
$^{3}M_{X}$FM MB^{1} DB^{1} P^{1}	33	33	35.5
$^{3}M_{X}$FM MB$^{1\text{-}2}$ DB^{1} P^{1}	7	40	7.5
$^{3}M_{X}$FM MB$^{1\text{-}*\text{-}2}$ DB^{1} P^{1}	7	47	7.5
$^{3}M_{X}$FM MB$^{1\text{-}2\text{-}1}$ DB^{1} P^{1}	6	53	6.5
$^{3}M_{X}$FM MB$^{1\text{-}*\text{-}1}$ DB^{1} P^{1}	4	57	4.3
$^{3}M_{X}$FM MB$^{1\text{-}2\text{-}1\text{-}2\text{-}1\text{-}2}$ DB^{1} P^{1}	4	61	4.3
$^{3}M_{X}$M MB$^{1\text{-}2\text{-}1\text{-}2}$ DB^{1} P^{1}	2	63	2.2
$^{3}M_{X}$M ^{DA}MB$^{1\text{-}2\text{-}1\text{-}2}$ DB^{1} P^{1}	2	65	2.2
$^{3}M_{X}$FM MB^{1} DB^{1} P^{1}	2	67	2.2
$^{3}M_{X}$FM MB$^{1\text{-}2\text{-}1}$ DB$^{1\text{-}2\text{-}1}$ P^{1}	2	69	2.2
$^{3}M_{X}$FM ^{DA}B$^{1\text{-}2}$ DB^{1} P^{1}	2	71	2.2
$^{3}M_{X}$M MB$^{1\text{-}2\text{-}1\text{-}2}$ DB^{1}P^{1}	1	72	1.1
$^{3}M_{X}$FM MB$^{1\text{-}2}$ DB^{1} P^{1}	1	73	1.1
^{3}MXFM MB$^{2\text{-}1\text{-}2}$ DB^{1} P^{1}	1	74	1.1
(T^{Meso}) $^{3}M_{X}$FM MB$^{2\text{-}1\text{-}2}$ DB^{1} P^{1}	1	75	1.1
$^{3}M_{X}$FM MB$^{2\text{-}1\text{-}2\text{-}1}$ DB^{1} P^{1}	1	76	1.1
$^{3}M_{X}$FM MB$^{1\text{-}2\text{-}3}$ DB^{1} P^{1}	1	77	1.1
$^{3}M_{X}$FM MB$^{1\text{-}2\text{-}3\text{-}4\text{-}2\text{-}1}$ DB^{1} P^{1}	1	78	1.1
$^{3}M_{X}$FM MB$^{2\text{-}1\text{-}2\text{-}3\text{-}2\text{-}1}$ DB^{1} P^{1}	1	79	1.1
$^{3}M_{X}$FM MB$^{1\text{-}*\text{-}3}$ DB^{1} P$^{1\text{-}*\text{-}1}$	1	80	1.1
$^{3}M_{X}$FM MB$^{1\text{-}2\text{-}3\text{-}2\text{-}1}$ DB^{1} P^{1}	1	81	1.1

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$^{3}M_{x}FM^{BR}\ MB^{2-1-2-1-2}\ DB^{1}\ P^{1}$	1	82	1.1
$^{3}M_{x}FM\ MB^{1-2-1-2-1}\ DB^{1}\ P^{1}$	1	83	1.1
$^{3}M_{x}FM\ MB^{1-2}\ DB^{1-2}\ P^{1}$	1	84	1.1
$^{3}M_{x}FM\ MB^{1-2-1-2-3—2}\ DB^{1}\ P^{1}$	1	85	1.1
$^{3}M_{x}FM\ ^{BR}MB^{1-2}\ DB^{1-2}\ P^{1-2}$	1	86	1.1
$^{3}M_{x}FM\ ^{DA}MB^{2}\ DB^{1-2}\ P^{1-2}$	1	87	1.1
$^{3}M_{x}FM\ MB^{2-*-2}\ DB^{1}\ P^{1}$	1	88	1.1
$^{3}M_{x}FM\ ^{DA}MB^{1-2-3-2}\ DB^{1-2-1-2}\ P^{1-2}$	1	89	1.1
$^{3}M_{x}FM\ MB^{2-*-2}\ DB^{1}\ P^{1-2}$	1	90	1.1
$^{3}M_{x}FM\ ^{DA}MB^{2-3-2-3}\ DB^{1-*-2}\ P^{1}$	1	91	1.1
$^{3}M_{x}FM\ MB^{2}\ DB^{1-*-3}\ P^{1}$	1	92	1.1
$^{3}M_{x}FM\ MB^{1}\ DB^{1-2}\ P^{1}$	1	93	1.1
Total	**93**	**93**	**100**

C-shaped configuration. A single tooth with a type 2 root fusion with joined root canals was also identified (n = 1/8; 12.5%). The remaining eight teeth displayed separated (/) root canal systems in each of the roots (n = 3/8; 37.5%).

To illustrate high dental root variation within South Africans, figures 4 and 5 below display a challenging clinical case of a South African individual where a maxillary first molar with a type 3 fusion was endodontically treated. Awareness of the possibility of highly variable root and canal morphology led a successful treatment outcome with apical healing (Figure 5 K and L):

Mandibular two-rooted first molars

Findings are summarized in Table IV. A total of 84 mandibular two-rooted first molars were analysed, with 52 different configurations calculated, and of this number, 39 were individual configurations (only one tooth per configuration,

Table III: Root canal configurations of fused three-rooted maxillary first molars according to Ahmed *et al.* excluding accessory canals, deltas, or pulp chamber canals (main canals only).

Configuration	Number of teeth	Cumulative total (number of teeth)	Percentage (%)	Separate (S) or joined (J) root canal network
(RF^{3}) $^{3}M_{x}FM\ ^{DA}MB^{1-2-3}\ DB^{1-*-2}/P^{1-2}$	1	1	12.5	S
(RF^{3}) $^{3}M_{x}FM\ MB^{2-1-2}\ DB//P^{1-*-2}$	1	2	12.5	J
(RF^{3}) $^{3}M_{x}FM\ MB^{2-1-2}\ DB^{1}/P^{1}$	1	3	12.5	S
(RF^{2}) $^{3}M_{x}FM\ MB//P^{1-2}\ DB^{1}$	1	4	12.5	J
(RF3, EP) $^{3}M_{x}FM\ MB^{1}\ DB^{1}/P^{1}$	1	5	12.5	S
(RF^{1}) $^{3}M_{x}FM\ ^{DA}MB//DB^{1-2-3}\ P^{1}$	1	6	12.5	J
(CsC^{1}, RF^{1}) $^{3}M_{x}FM\ ^{DA}MB//DB^{1-*-3}\ P^{1}$	1	7	12.5	J
(RF^{3}) $^{3}M_{x}FM\ MB^{1}\ DB//P^{1-2}$	1	8	12.5	J
Total	**8**	**8**	**100**	

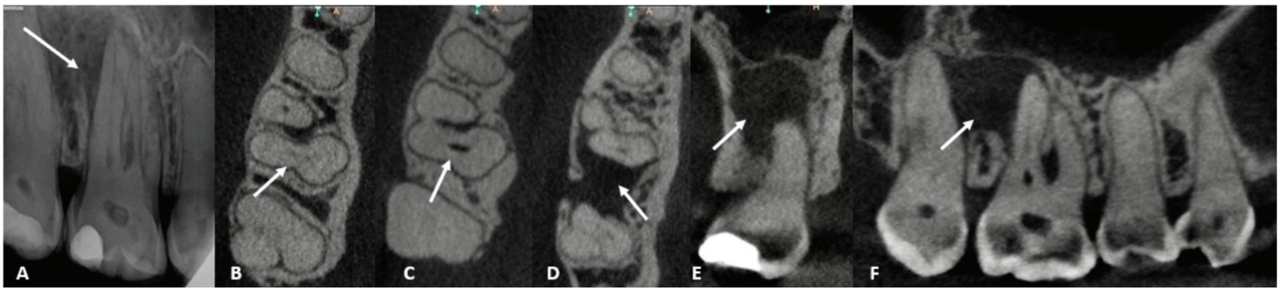

Figure 4: A 39-year-old female patient presented with a non-vital right maxillary first molar; **(A)** Pre-operative periapical radiograph showing evidence of a periapical lesion on the distal aspect of the disto-buccal root (arrow); **(B)** A coronal axial slice from a high-resolution CBCT scan revealed that the disto-buccal root and the palatal root were fused together, with evidence of two canal orifices (arrow) (disto-buccal and palatal) at this level; **(C)** A mid-root axial slice of the CBCT scan demonstrated that the two canals merged into one large canal (arrow); **(D)** An apical axial slice of the CBCT scan illustrated that the merged root still contained a single canal, with a significant area of bone destruction (arrow) extending up to the mesio-buccal root of the vital second molar. The lesion also extended at this level, resulting in the destruction of the cortical buccal plate; **(E)** A coronal slice of the CBCT scan of the fused root showed extensive bone destruction surrounding the root (arrow); **(F)** A sagittal slice of the CBCT scan illustrated the extent of the bone destruction between the fused root and the mesio-buccal root of the second molar (arrow) (clinical case courtesy of Prof. PJ van der Vyver).

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Figure 5: (G) A periapical radiograph illustrating the determination of the lengths of the two root canal systems. It was noted that the apex of the fused root canal system was open beyond an ISO size of 55, and it was decided to use Mineral Trioxide Aggregate (MTA) (Dentsply Sirona) for apex closure in this root; **(H)** A periapical radiograph confirming the fit of the ProTaper Ultimate F2 gutta-percha cone (Dentsply Sirona) in the mesio-buccal root canal system, as well as the stainless steel plugger in the fused root canal system, indicating the level where MTA will be packed (after root canal preparation with the ProTaper Ultimate system (Dentsply Sirona): the fused canal with ProTaper Ultimate FXL and the mesio-buccal root canal system with ProTaper Ultimate F2; **(I)** A post-obturation periapical radiograph following irrigation and obturation of the mesio-buccal root canal system using the continuous wave of condensation technique. MTA was packed into the apical 6 mm of the fused canal system; **(J)** The final post-obturation periapical radiograph following the obturation of the rest of the fused canal with gutta-percha; **(K)** A postoperative periapical radiograph taken after 8 months, demonstrating good healing of the periapical lesion; **(L)** A sagittal slice of the CBCT scan illustrated good healing of the periapical lesion (arrow) after 8 months (clinical case courtesy of Prof. PJ van der Vyver).

n = 39/84, 46.4%), and 13 configurations occurred in more than one tooth. The most common configurations were $^{2}M_{D}FM\ M^{1-2}\ D^{1}$ (*n* = 8/84, 9.5%), followed by $^{2}M_{D}FM\ M^{1}\ D^{1}$ (*n* = 6, 7.1%), $^{2}M_{D}FM\ M^{1-2-1-2}D^{1}$ (*n* = 4/84, 4.8%) and $^{2}M_{D}FM\ M^{1-*-1}D^{1}$ (*n* = 4/84, 4.8%).

To illustrate the high degree of variability within the root canal system within South Africans a mandibular first molar figure 6 below display a challenging clinical case of a South African individual where a mandibular first molar with a $^{2}MDFM\ M^{2}D^{1-2-3}$ configuration was endodontically treated:

Table IV: Root canal configurations of two-rooted mandibular first molars according to Ahmed *et al.* excluding accessory canals, deltas, or pulp chamber canals (main canals only).

Configuration	Number of teeth	Cumulative total (number of teeth)	Total percentage (%)
$^{2}M_{D}FM\ M^{1-2}\ D^{1}$	8	8	9.5
$^{2}M_{D}FM\ M^{1}\ D^{1}$	6	14	7.1
$^{2}M_{D}FM\ M^{1-2-1-2}\ D^{1}$	4	18	4.8
$^{2}M_{D}FM\ M^{1-*-1}\ D^{1}$	4	22	4.8
$^{2}M_{D}FM\ M^{2-1}\ D^{1}$	3	25	3.6
$^{2}M_{D}FM\ M^{1-2-1-2-1}\ D^{1}$	3	28	3.6
$^{2}M_{D}FM\ ^{DA}M^{1-2}\ D^{1}$	3	31	3.6
$^{2}M_{D}FM\ M^{1-*-2}\ D^{1}$	3	34	3.6
$^{2}M_{D}FM\ ^{DA}M^{1-*-2}\ D^{1}$	3	37	3.6
$^{2}M_{D}FM\ ^{DA}M^{1-2-1-2}\ D^{1}$	2	39	2.4
$^{2}M_{D}FM\ M^{1-2-1}\ D^{1}$	2	41	2.4
$^{2}M_{D}FM\ M^{2-*-2}\ D^{1}$	2	43	2.4
$^{2}M_{D}FM\ ^{DA}M^{1-*-3}\ D^{1-2}$	2	45	2.4
$^{2}M_{D}FM\ ^{DA}M^{2-*-2}\ D^{1}$	1	46	1.2
$^{2}M_{D}FM\ M^{2-1-2}\ D^{1}$	1	47	1.2
$^{2}M_{D}FM\ M^{2-1-2}\ D^{1}$	1	48	1.2
$^{2}M_{D}FM\ M^{1-*-2}\ D^{1-2}$	1	49	1.2
$^{2}M_{D}FM\ ^{DA}\ M^{1-*-2}\ ^{DA}\ D^{1-2}$	1	50	1.2
$^{2}M_{D}FM\ M^{1-*-3}\ D^{1}$	1	51	1.2
$^{2}M_{D}FM\ M^{2}\ D^{1-2-1-2}$	1	52	1.2
$^{2}M_{D}FM\ ^{BR}\ M^{1-2}\ ^{DA}\ D^{1-*-3}$	1	53	1.2
$^{2}M_{D}FM\ M^{2-3-2}\ D^{1}$	1	54	1.2
$^{2}M_{D}FM\ ^{DA}M^{2-1-2-3-2}\ D^{1-2-1}$	1	55	1.2
$^{2}M_{D}FM\ M^{1-2-1-2}\ D^{1-2}$	1	56	1.2
$^{2}M_{D}FM\ ^{BR}\ M^{2}\ ^{DA}\ D^{1-*-3}$	1	57	1.2
$^{2}M_{D}FM\ M^{1-*-1}\ D^{1-2}$	1	58	1.2
$^{2}M_{D}FM\ ^{DA}M^{1-2-3}\ D^{1}$	1	59	1.2

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$^{2}M_{D}FM\ M^{1-2-3-2-1}\ D^{1}$	1	60	1.2
$^{2}M_{D}FM\ {}^{DA}M^{1-2}\ D^{1-2}$	1	61	1.2
$^{2}M_{D}FM\ M^{1-*-1}\ D^{1-2-1}$	1	62	1.2
$^{2}M_{D}FM\ M^{1-2-1-2-1}\ D^{1-*-2}$	1	63	1.2
$^{2}M_{D}FM\ M^{1-*-3}\ D^{1-2-1-2-1-2}$	1	64	1.2
$^{2}M_{D}FM\ M^{1-2-3-4-2-4}\ D^{1-*-2}$	1	65	1.2
$^{2}M_{D}FM\ M^{2}\ D^{1-2-1}$	1	66	1.2
$^{2}M_{D}FM\ {}^{DA}M^{1-2-3-2-1}\ D^{1}$	1	67	1.2
$^{2}M_{D}FM\ M^{1-3-2-3-4}\ D^{1}$	1	68	1.2
$^{2}M_{D}FM\ {}^{DA}M^{1-2}\ D^{1-2-1-2}$	1	69	1.2
$^{2}M_{D}FM\ {}^{DA}M^{2-3}\ D^{2-1-2-1-2}$	1	70	1.2
$^{2}M_{D}FM\ {}^{DA}M^{1-3-2}\ D^{1}$	1	71	1.2
$^{2}M_{D}FM\ M^{1-3-2-1}\ D^{1}$	1	72	1.2
$^{2}M_{D}FM\ M^{1-3-2-3-2-1}D^{1}$	1	73	1.2
$^{2}M_{D}FM\ M^{2-1-2-1-2}\ D^{1}$	1	74	1.2
$^{2}M_{D}FM\ {}^{BR}M^{2}\ {}^{DA}D^{1-*-3}$	1	75	1.2
$^{2}M_{D}FM\ {}^{BR}M^{2-3}\ {}^{DA}D^{1-*-4}$	1	76	1.2
$^{2}M_{D}FM\ M^{2}\ D^{1-*-1}$	1	77	1.2
$^{2}M_{D}FM\ M^{2-1-2}\ D^{1-2-1-2-1}$	1	78	1.2
$^{2}M_{D}FM\ {}^{DA}M^{1-2-1-2-3}\ D^{1}$	1	79	1.2
$^{2}M_{D}FM\ {}^{DA}M^{1-2-3-2-3}\ D^{1-*-2}$	1	80	1.2
$^{2}M_{D}FM\ {}^{DA}M^{1-2}\ D^{1-2-3-2-1-2}$	1	81	1.2
$^{2}M_{D}FM\ M^{1-2-1-2-3}\ D^{1}$	1	82	1.2
$^{2}M_{D}FM\ {}^{DA}M^{1-*-2}\ D^{1-*-2}$	1	83	1.2
$^{2}M_{D}FM\ M^{1-*-2}\ D^{1-*-2}$	1	84	1.2
Total	**84**	**84**	**100**

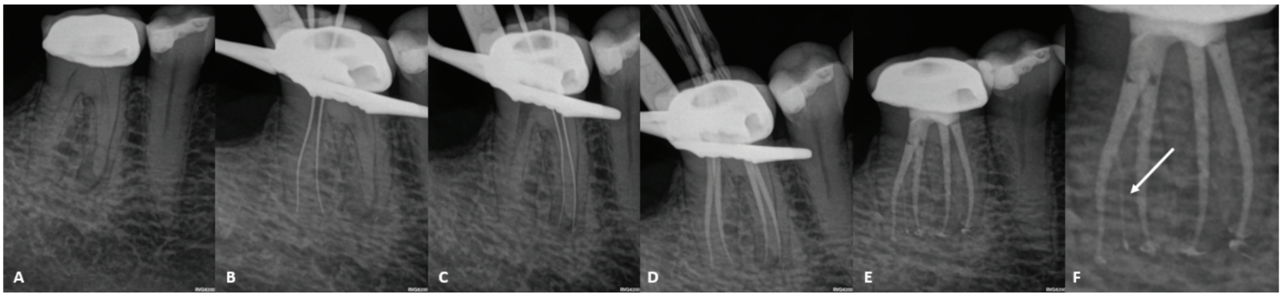

Figure 6: (A) A 45-year-old male patient presented with a non-vital right mandibular first molar; **(B)** Periapical radiograph illustrating the length determination of the two distal root canal systems; **(C)** Periapical radiograph illustrating the length determination of the two mesial root canal systems; **(D)** Periapical radiograph confirming the fit of yellow WaveOne Gold gutta-percha cones following the root canal preparation of the four root canal systems, using a yellow WaveOne Gold file; **(E)** Post-obturation periapical radiograph after irrigation and obturation of the four root canal systems via the continuous wave of condensation technique; **(F)** Note the apical bifurcation of the distobuccal root canal system in the mid-root region (arrow) (clinical case courtesy of Prof. PJ van der Vyver)..

Mandibular three-rooted first molars

Findings are summarized in Table V. In addition to the 52 configurations noted for the two-rooted mandibular first molars, two other configurations were observed in the two, three-rooted mandibular first molars evaluated. No common configurations or joined root canals were noted in the three-rooted teeth. One tooth did not have any root canal present in the additional root (n = 1/2, 50%).

Table V: Root canal configurations of three-rooted mandibular first molars according to Ahmed *et al.* excluding accessory canals, deltas, or pulp chamber canals (main canals only).

Configuration	Number of teeth	Cumulative total (number of teeth)	Percentage (%)
(RE^{II}) $^{3}M_{D}FM\ {}^{DA}M^{1-*-2}\ DB^{1}\ DL^{1}$	1	1	50
($RE^{Conical}$) $^{3}M_{D}FM\ M^{1-*-1}\ DB^{1}\ DL^{0}$	1	2	50
Total	**2**	**2**	**100**

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Root canal configurations including accessory canals, according to the Ahmed *et al.* classification.

The addition of accessory canals to the previously calculated configurations resulted in configurations that were mostly individualised with only a few notable similarities. A total of 97 and 85 unique configurations were respectively found in the 101 maxillary and 86 mandibular teeth. In the separate three-rooted maxillary molars, the only similarities were $^{3}M_{X}FM\ MB^{1(A2)}\ DB^{1(A1)}\ P^{1}$ (*n* = 4/93, 4.3%) and $^{3}M_{X}FM\ MB^{1(A1)}\ DB^{1(A1)}\ P^{1}$ (*n* = 2/93, 2.2%). In two-rooted mandibular molars, only $^{2}M_{D}FM\ M^{1}D^{1}$ (*n*=2/84, 2.4%) was noted. No similarities were noted in the maxillary fused-rooted or in the mandibular three-rooted groups. For illustrative purposes to determine the root canal configuration, figure 6 below illustrates a clinical case where a mandibular first molar of a South African individual was endodontically treated. Note the presence of patent accessory canals (A1) in the apical region of the roots:

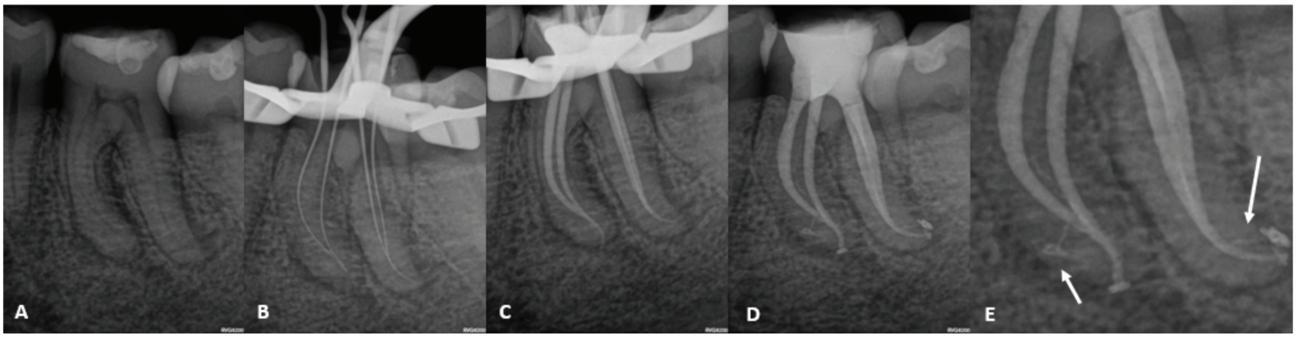

Figure 7: **(A)** A 52-year-old female patient presented with a non-vital two-rooted left mandibular first molar; **(B)** Periapical radiograph illustrating the length determination of the two mesial and two distal root canal systems; **(C)** Periapical radiograph confirming the fit of yellow ProTaper Ultimate gutta-percha cones (Dentsply Sirona) following the root canal preparation of the four root canal systems, using the ProTaper Ultimate system; **(D)** Post-obturation periapical radiograph indicating a $^{2}MDFM\ M^{2\text{-}1(A1)}D^{2\text{-}1(A1)}$ configuration following irrigation and obturation via the continuous wave of condensation technique; **(E)** Note the apical lateral canals in the mesial (M) and distal (D) root canal systems (arrows) (clinical case courtesy of Prof. PJ van der Vyver).

DISCUSSION

Endodontic treatment has been established as a suitable method to treat endodontically affected teeth to keep them functional and symptom-free.[1] However, root canal morphology can be extremely complex. Unfortunately, it has been shown that it can be challenging to reach and disinfect all areas of an infected root canal system.[34] Furthermore, any area of a root canal that is not disinfected has the potential to cause treatment failures.[1,35] The retention of the first molar has been recognized as important in the preservation of the occlusal scheme.[36] Unfortunately, the maxillary and mandibular first permanent molars in particular have been considered to display complex internal morphology and can pose formidable treatment challenges.[35,37]

Recently, the Ahmed *et al.* classification system, which provides clear guidelines and terminology for CBCT and micro-CT scans, was introduced.[7,11,12] Complex root and canal morphologies as well as accessory root canal anatomy can also be included.[12,13] In the current investigation, $^{3}M_{X}FM\ MB^{1}DB^{1}P^{1}$ was the most common maxillary main canal configuration (35.5%). Although the Ahmed *et al.* classification is different from the Vertucci classification system, the $^{3}M_{X}FM\ MB^{1}DB^{1}P^{1}$, $^{3}M_{X}FM\ MB^{1}DB^{1\text{-}2}P^{1}$, $^{3}M_{X}FM\ ^{(1\text{-}0)}MB^{1}DB^{1}P^{1}$, $(RF^{3},EP)^{3}M_{X}FM\ MB^{1}DB^{1}/P^{1}$, and $(RF^{3})^{3}M_{X}FM\ MB^{1}DB//P^{1\text{-}2}$ configurations calculated in this investigation indicate a single canal from orifice to apex (O-C-F) in the MB root. The combined prevalence for a single canal in a MB root (separate and fused-rooted molars) is 37.6% (*n* = 38/101), which is lower than the equivalent prevalence of Vertucci Type I configurations found in a Ugandan sample[5], but similar to a Russian sample[38]. The different methodologies used in these studies (CBCT and clearing/staining) and the current investigation (micro-CT) may have contributed towards the variable results.

Studies where the Ahmed *et al.* classification system were used are scarce. In a CBCT study on individuals from Chile, the authors found that the $^{2}M_{D}FM\ M^{1}\ D^{1}$ configuration was present in 13.4% of mandibular first molars.[39] In contrast to the current investigation, the same configuration was found in 7.1% in mandibular molars. The difference might be attributed to difference in population, genetics, or perhaps socio-economic factors. However, a methodological reason could also be envisioned. In the Chilean study, the landmarks used to describe the configurations were not specified, in contrast to the current investigation where the methodology of Jonker *et al.* (2024)[18] was followed. Ahmed *et al.* (2021) also highlighted the fact that results from morphological studies may be subjective, and that careful consideration should be given when comparisons are made.[7]

Even though the Ahmed *et al.* terminology considered all previous descriptions for accessory root canal anatomy, a range of pathway angles were noted by observing figures and illustrations from previous work from Ahmed *et al.*[7,13,28,29] A clear distinction between accessory canals and canal bifurcations was not described. In our investigation, it was observed that accessory canals followed a variety of angles and rarely a perpendicular pattern. This could indicate that the visual distinction between apical accessory canals and apical bifurcations based on relative angles may include a degree of subjectivity. In the current study, the relative size and diameter of the canal was used to distinguish between accessory canals and canal bifurcations and high-resolution imaging provided sufficient visual information to make the distinction. In-depth measurements and further descriptors of both accessory canals and canal bifurcations may be beneficial for consideration for future projects.

Despite the possible limitations, the current study followed a repeatable and standard method to determine the location of the orifice and the point of origin for root canal configurations based on previous work by Jonker *et al.*[18] In addition, clear guidelines were followed to distinguish between accessory canals and apical bifurcations, and between single or double canals connected with an isthmus. Clear descriptors were also provided in the Glossary of Terms (Table I) for different types of accessory canals. The authors suggest that by following the methodology and terminology described in this study, a more accurate comparison between similar future studies is possible. The current investigation is the first study reporting on root canal configurations of main canals and complex configurations using micro-CT and the Ahmed *et al.* classification system in a South African population.

One of the benefits of the Ahmed *et al.* classification system is the fact that configurations can be adjusted to suit the purpose of a study.[7] The calculation of configurations in the current project included firstly main canals and secondly accessory root canal anatomy. Many configuration types were calculated in both maxillary and mandibular molars: 41 configurations in the maxilla and 54 in mandible for main canal pathways only. A total of 183 individualised configurations were determined, and only two common configurations were noted once fine root canal anatomy was included: one in maxillary molars and one in mandibular molars. Accessory root canal anatomy cannot be ignored as these pathways could potentially provide a direct communication between the peri-apical and peri-radicular tissues and the root canal system. Causative organisms can obtain their nutrients from these channels leading to treatment failure.[40]

Buchanan *et al.* (2023)[41], in a CBCT study on mandibular second molars in South Africans, made a similar observation on the limitations of the Ahmed *et al*. classification system. Their calculations also resulted in many configurations when using the Ahmed *et al.* classification system to report on root canal configurations. The number of configurations in the current study indicates the diverse nature of the root canal complex of first molars in South Africans, confirming what other studies have reported in other population groups.[5,19]

Modern endodontic systems can prepare root canals with remarkable speed to reduce clinical chair time[1], but considering the findings from this project, it is highly advisable to place a special emphasis on irrigation regimes. Despite tremendous advances, it is virtually impossible for current root canal instrumentation to reach all areas of the root canal system and in particular complexities. Therefore, optimal chemical and mechanical disinfection techniques are instrumental to long term survival of an affected tooth.[42] A proper three-dimensional seal of the prepared and disinfected root canal spaces is also required.[1]

Limitations of the current study include for example the sample size, as a convenience sampling method was used on an already available archived micro-CT scan collection. Further, only first molars of one population group were included and investigations on other tooth types and populations and comparisons between populations might be considered for future projects. Dried human skulls were used which present with inevitable micro-crack formation leading to possible confusion between accessory canal anatomy and micro-cracks. This limitation was addressed using a masking or multiple slice editing technique described by Ahmed *et al.* (2022).[28] Micro-CT scanning was done on the entire skeletonized maxillae and mandibulae with high voxel sizes (between 40.3 μm and 74.2 μm). It has been reported that voxel sizes on extracted teeth range between <10 μm and 30 μm.[28] At higher voxel sizes, the patency of some accessory canals may not be clearly visible. Lastly, the authors acknowledge the possibility of a degree of subjectivity in the identification of root canal anatomy.

The demonstrated root canal configurations were found to be complex and important to consider not only in the South African context but also globally. Many South Africans emigrate to other countries, including the United Kingdom and Europe. Since 2010, intra-African migrations showed the second highest increase from all regions considered and more specifically Africa-Europe migrations increased by 26.0%. According to the Mo Ibrahim Foundation[43], the number of African migrants to Europe was 40.6 million in 2020. Statistics estimate that 6% of South Africans living in the United Kingdom were from African descent.[44] More locally in South Africa, a study investigated the prevalence of emergency procedures (including root canal treatments) performed at their institution. The author determined that between 90% and 91% of their patient base are from African descent.[45] Therefore, any clinician may be required to endodontically treat a first molar of these individuals.

Root canal configurations in South Africans were found to be diverse. The Ahmed *et al.* classification system classified all main root canal configurations. However, the addition of accessory canals and fine detail significantly increased the complexity, resulting in several additional configurations. It can be speculated that similar findings might exist in other populations and molars. A need has been identified to develop a classification system or propose modifications to the current Ahmed *et al*. system to accommodate complex configurations in a practical manner.

DECLARATION

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CONFLICT OF INTEREST:

None

REFERENCES

1. Vertucci FJ. Root canal morphology and its relationship to endodontic procedures. Endod Top. 2005; 10: 3–29. DOI: 10.1111/j.1601-1546.2005.00129.x
2. Versiani MA, De-Deus G, Vera J, et al. 3D mapping of the irrigated areas of the root canal space using micro-computed tomography. Clin Oral Invest. 2015; 19: 859–66. DOI: 10.1007/s00784-014-1311-5
3. Blattner TC, George N, Lee CC, Kumar V, Yelton CDJ. Efficacy of cone-beam computed tomography as a modality to accurately identify the presence of second mesiobuccal canals in maxillary first and second molars: a pilot study. J Endod. 2010; 36: 867-70. DOI: 10.1016/j.joen.2009.12.023
4. Degerness RA, Bowles WR. Dimension, anatomy and morphology of the mesiobuccal root canal system in maxillary molars. J Endod. 2010; 36: 985–9. DOI: 10.1016/j.joen.2010.02.017
5. Rwenyonyi CM, Kutesa AM, Muwazi LM, Buwembo W. Root and canal morphology of maxillary first and second permanent molar teeth in a Ugandan population. Int Endod J. 2007; 40: 679–83. DOI: 10.1111/j.1365-2591.2007.01265.x
6. Buchanan GD, Gamieldien MY, Tredoux S, Vally ZI. Root and canal configurations of maxillary premolars in a South African subpopulation using cone beam computed tomography and two classification systems. J Oral Sci. 2020; 62:93–7. DOI: 10.2334/josnusd.19-0160
7. Ahmed HMA, Ibrahim N, Mohamad NS, et al. Application of a new system for classifying root and canal anatomy in studies involving micro-computed tomography and cone beam computed tomography: explanation and elaboration. Int Endod J. 2021; 54: 1056–082. DOI: 10.1111/iej.13486
8. Versiani MA, Pécora JD, de Sousa-Neto MD. Root and root canal morphology of four-rooted maxillary second molars: a micro–computed tomography study. J Endod. 2012; 38: 977–82. DOI: 10.1016/j.joen.2012.03.026
9. Briseño-Marroquín B, Paqué F, Maier K, Willershausen B, Wolf TG. Root canal morphology and configuration of 179 maxillary first molars by means of micro–computed tomography: an ex vivo study. J Endod. 2015; 41: 2008–13. DOI: 10.1016/j.joen.2015.09.007
10. Ahmed HMA, Hashem AAR, Dummer PMH. Application of a new system for classifying root and canal anatomy in clinical practice–explanation and elaboration. Eur Endod J. 2021; 6: 132–42. DOI: 10.14744/eej.2021.38257

www.sada.co.za / SADJ Vol. 80 No.5
https://doi.org/10.17159/sadj.v80i05.21365

11. Ahmed HMA, CheAb Aziz ZA, Azami NH *et al.* Application of a new system for classifying root canal morphology in undergraduate teaching and clinical practice: a national survey in Malaysia. Int Endod J. 2021; 53: 871–9. DOI: 10.1111/iej.13271
12. Ahmed HMA, Versiani MA, De-Deus G, Dummer PMH. A new system for classifying root and root canal morphology. Int Endod J. 2017; 50: 761–70. DOI: 10.1111/iej.12685
13. Ahmed HMA, Neelakantan P, Dummer PMH. A new system for classifying accessory canal morphology. Int Endod J. 2018; 51: 164–76. DOI: 10.1111/iej.12800
14. Ahmed HMA, Dummer PMH. Advantages and applications of a new system for classifying roots and canal systems in research and clinical practice. Eur Endod J. 2018; 3: 9–17. DOI: 10.5152%2Feej.2017.17064
15. Martins JN, Nole C, Ounsi HF, et al. Worldwide assessment of the mandibular first molar second distal root and root canal: a cross-sectional study with meta-analysis. J Endod. 2022; 48: 223–33. DOI: 10.1016/j.joen.2021.11.009
16. Hatipoglu FP, Magat G, Hatipoglu Ö, et al. Assessment of the prevalence of middle mesial canal in mandibular first molar; a multinational cross-sectional study with meta-analysis. J Endod. 2023; 49: 549-58. DOI: 10.1016/j.joen.2023.02.012
17. Fernandes NA, Herbst D, Postma TC, Bunn BK. The prevalence of second canals in the mesiobuccal root of maxillary molars: a cone beam computed tomography study. Aust Endod J. 2019; 45: 46-50. DOI: 10.1111/aej.12263
18. Jonker CH, Lambourn G, Oettlé AC, Foschi F, Theye C, L'Abbé EN. A new methodology to determine the orifice for root canal configurations in first permanent molar root and canal morphologies using micro-computed tomography. J Clin Med. 2024; 13: 71. DOI: 10.3390%2Fjcm13010071
19. Sert S, Bayirli G. Evaluation of the root canal configurations of the mandibular and maxillary permanent teeth by gender in the Turkish population. J Endod. 2004; 30: 391–8. DOI: 10.1097/00004770-200406000-00004
20. Tredoux S, Warren N, Buchanan GD. Root and canal configurations of mandibular first molars in a South African subpopulation. J Oral Sci. 2021; 63: 252–6. DOI: 10.2334/josnusd.20-0651
21. Cuschieri S. The STROBE guidelines. Saudi J Anaesth. 2019; 13(Suppl 1): S31-4. DOI: 10.4103/sja.SJA_543_18
22. Jonker CH, L'Abbé EN, van der Vyver PJ, Zahra D, Oettlé AC. A micro-computed tomographic evaluation of maxillary first molar root canal morphology in Black South Africans. J Oral Sci. 2024; 66: 151-6. DOI: 10.2334/josnusd.24-0074
23. L'Abbé EN, Krüger GC, Theye CE, Hagg AC, Sapo O. The Pretoria bone collection: a 21st century skeletal collection in South Africa. J Foren Sci. 2021; 1: 220–7. DOI: 10.3390/forensicsci1030020
24. Hoffman, J.W.; De Beer, F.C. Characteristics of the Micro-Focus X-Ray Tomography Facility (MIXRAD) at Necsa in South Africa. In Proceedings of the 18th World Conference on Nondestructive Testing, Durban, South Africa, 16–20 April 2012.
25. Westenberger, P. Avizo—Three-Dimensional Visualization Framework. In Proceedings of the Geoinformatics—Data to Knowledge Conference, Potsdam, Germany, 11–13 June 2008.
26. Krasner P, Rankow HJ. Anatomy of the pulp chamber floor. J Endod. 2004; 30: 5–16. DOI: 10.1097/00004770-200401000-00002
27. Roerdink JBTM, Meijster A. The watershed transform: definitions, algorithms and parallelization strategies. Fundam Inform 2000; 41: 187–228. DOI: 10.3233/FI-2000-411207
28. Ahmed HMA. A critical analysis of laboratory and clinical research methods to study root and canal anatomy. Int Endod J. 2022; 55: 229–80. DOI: 10.1111/iej.13702
29. Ahmed HMA, Dummer PM. A new system for classifying tooth, root and canal anomalies. Int Endod J. 2018; 51: 389–404. DOI: 10.1111/iej.12867
30. Zhang Q, Chen H, Fan B, Fan W, Gutmann JL. Root and root canal morphology in maxillary second molar with fused root from a native Chinese population. J Endod. 2014; 40: 871–5. DOI: 10.1016/j.joen.2013.10.035
31. Fan W, Fan B, Gutmann JL, Cheung GS. Identification of C-shaped canal in mandibular second molars. Part I: radiographic and anatomical features revealed by intraradicular contrast medium. J Endod. 2007; 33: 806–10. DOI: 10.1016/j.joen.2007.04.007
32. Song JS, Choi H-J, Jung I-Y, Jung H-S, Kim S-O. The prevalence and morphologic classification of distolingual roots in the mandibular molars in a Korean population. J Endod. 2010; 36: 653–7. DOI: 10.1016/j.joen.2009.10.007
33. Xu T, Gao X, Fan W, Fan B. Micro-computed tomography evaluation of the prevalence and morphological features of apical bifurcations. J Dent Sci. 2020; 15: 22-7. DOI: 10.1016/j.jds.2019 .05.005
34. Versiani MA, Ordinola-Zapata R. Root canal anatomy: implications in biofilm disinfection. The root canal biofilm, 1st ed. Berlin: Springer, 2015: 155 – 87.
35. Versiani MA, Ordinola-Zapata R, Keles A, et al. Middle mesial canals in mandibular first molars: a micro-CT study in different populations. Arch Oral Biol. 2016; 61: 130–7. DOI: 10.1016/j.archoralbio.2015.10.020
36. Zhang X, Xiong S, Ma Y, et al. A cone-beam computed tomographic study on mandibular first molars in a Chinese subpopulation. PLoS ONE. 2015; 10: e0134919. DOI: 10.1371%2Fjournal.pone.0134919
37. Martins JNR, Alkhawas MAM, Altaki Z, et al. Worldwide analyses of maxillary first molar second mesiobuccal prevalence: a multicenter cone-beam computed tomographic study. J Endod. 2018; 44: 1641-9. DOI: 10.1016/j.joen.2018.07.027
38. Razumova S, Brago A, Khaskhanova L, Barakat H, Howijieh A. Evaluation of anatomy and root canal morphology of the maxillary first molar using the cone-beam computed tomography among residents of the Moscow region. Contemp Clin Dent. 2018; 9: S133-6. DOI: 10.4103/ccd.ccd_127_18
39. Abarca J, Duran M, Parra D, Steinfort K, Zaror C, Monardes H. Root morphology of mandibular molars: a cone-beam computed tomography study. Folia morphol. 2020; 79: 327–32. DOI: 10.5603/FM.a2019.0084
40. Siqueira JF, Rôças IN. Clinical implications and microbiology of bacterial persistence after treatment procedures. J Endod. 2018; 34: 1291-1301. DOI: 10.1016/j.joen.2008.07.028
41. Buchanan GD, Gamieldien MY, Fabris-Rotelli I, van Schoor A, Uys A. Investigation of mandibular second molar root and canal morphology in a Black South African population using cone-beam computed tomography and two classification systems. J Oral Sci. 2023; 23: 226-31. DOI: 10.2334/josnusd.23-0123
42. De-Deus G, Belladonna FG, Silva EJNL, et al. Micro-CT evaluation of non-instrumented canal areas with different enlargements performed by NiTi systems. Braz Dent J. 2015; 26: 624–9. DOI: 10.1590/0103-6440201300116
43. Mo Ibrahim Foundation (MIF) (2022). Facts and Figures on African Migration. Africa Europe Foundation. Accessed 6 October, 2023. https://mo.ibrahim.foundation/sites/default/files/2022-02/aef_summit_african-migrations.pdf.
44. Statistics South Africa (2011) Formal Census 2011 [PDF of Internet]. South Africa. https://www.statssa.gov.za//publcations/P03014/P030142011.pdf. Accessed 27 February 2023.
45. Maaga MA. Profile of patients treated in the Careline Clinic of the Medunsa Oral Health Centre [dissertation]. Ga-Rankuwa (Gauteng): University of Limpopo; 2013.