Dento-alveolar measurements and histomorphometric parameters of maxillary and mandibular first molars, using micro-CT

Running head: Micro-CT study of maxillary and mandibular first molars and sockets

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Conflict of Interest Statement

CT, AH, ACO, MS have nothing to disclose. TC reports personal fees from Southern Implants (employee), outside the submitted work. SV was supported with a grant from Southern Implants to conduct research, outside the submitted work.

Author Contribution Statement

CT designed research, contributed acquisition of micro-CT data, performed data analysis/interpretation and drafting of the manuscript. AH and SV designed research and provided critical revision of the manuscript. TC designed research, contributed data analysis/interpretation and critical revision of the manuscript. ACO and MS contributed data interpretation and critical revision of the manuscript. All authors have approved the final version to be published.

Abstract

Background: Micro-CT is a high-resolution, non-invasive and non-destructive imaging technique, currently acknowledged as a gold standard modality for assessing quantitatively and objectively dental morphology and bone microarchitecture parameters.

Purpose: The aim of this study was to analyze critical dental and periodontal measurements characterizing the mandibular (MandFM) and maxillary (MaxFM) first molar architecture, as well as the corresponding bony socket, using micro-CT.

Materials and Methods: Thirty-eight human dried skulls (22-76 years) were scanned to enable the virtual analysis of 61 first molars. Depending on the type of measurement, the parameters were recorded on two-dimensional sections or directly on three-dimensional models. Tooth morphology was described by four aspects (e.g., tooth width, trunk length, root length and root span), while the socket architecture was assessed by buccal plate thicknesses and bone density measurements.

Results: Minimum, maximum and mean distances as well as cortical and trabecular bone densities were recorded in MandFM and MaxFM. It is noteworthy that the buccal plate thickness was found to be less than 1 mm in more than 55% of cases in MaxFM, whereas only in 20.8% of cases in MandFM (and even 0% at two sites). A wide range of bone densities was observed and the comparison between MandFM and MaxFM did not show a significant difference. Furthermore, cortical densities were negatively correlated with aging, while trabecular densities were not influenced.

Conclusions: Using micro-CT, three-dimensional aspects of the human first molar morphology and microstructural parameters of the surrounding bone were evaluated in the mandible and in the maxilla. These comprehensive measurements and their correlation with aging may be of great importance for the use of immediate implant placement in molar extraction sockets and thus the potential long-term success of this treatment modality.

Keywords

Buccal plate, bone density, extraction socket, first molars, immediate implant, implant stability, mandible, maxilla, micro-CT

Introduction

Generally, molars are reported to be the most frequently extracted teeth.[1,2] First molars are the first teeth to permanently erupt and are therefore prone to decay (e.g., caries) at an earlier age than other tooth types.[3] Loss of first molars has severe consequences on the mastication process and its efficiency, as first molars are the largest and strongest teeth, located near the center of the dental arches. Furthermore, first molars play a major role in maintaining continuity within the arch and keeping the teeth in a proper alignment.[4] Thus, the replacement of lost first molars is of particular importance, and should be performed without much delay.

The placement of dental implants at the time of tooth extraction was introduced in 1989 and is now well established.[5,6] However, immediate implant placement into a molar socket is still a challenge for the clinician,[7,8] mainly because of the increased peripheral dimensions but also because of the residual interradicular bone hindering primary stability, and so the critical positioning of the implant.[6,8–13] Other possible anatomical shortcomings include inadequate buccal plate thickness and poor bone density.[14–18] Moreover, as for delayed implant placement, the close proximity of the maxillary sinus, the inferior alveolar nerve, and/or the mandibular lingual canal may be of concern as well.[19–24] Parameters describing and quantifying the three-dimensional morphology of the tooth and of the socket and microstructure of the surrounding bone could provide vital information for clinicians.[9,10,13]

Analysis of the microstructure of the maxillary and mandibular periodontal bone as well as dental parameters may be performed on three-dimensional (3D) models computed from Micro-Focus X-Ray Computed-Tomography (micro-CT) scans. Furthermore, even if micro-CT cannot be employed in a daily clinical dental setting, this imaging technique is often used as a gold standard modality for dental research[25–29] and for osseous microstructure assessment[17,30,31] as it renders high-resolution results non-invasively and non-destructively.[25,32,33] Different types of variables can be obtained from micro-CT scans: linear measurements between landmarks on 3D models, or on 2D sections, assessing tooth or bone morphology; and histomorphometric parameters evaluating bone density and microarchitecture. These parameters, such as bone volumetric fraction (BV/TV), bone volume (BV) and total volume (TV) previously defined by Parfitt,[34] provide automatic and objective bone density information.[17,35]

Several studies have used micro-CT to assess bone density and microarchitecture of alveolar bone in human maxillae and mandibles on biopsies from cadaver specimens[17,31,36-38] or from patients.[15,30,33] However, in the literature researched, the cadaver-based studies were all performed on less than 30 specimens,[17,31,36] or even on a single specimen only.[37,38] Moreover, both patient and cadaver-based studies analyzed biopsies extracted from edentulous sites only. In a comparative study between CBCT and micro-CT techniques, Van Dessel et al[39] measured histomorphometric parameters at non-edentulous sites. However, the study focused on single-rooted teeth and was performed on a single cadaver specimen.

Thus, to date, very limited data is available on the microstructure of the cortical and trabecular bone surrounding the first molars, or even density of the interradicular bone. Furthermore, none of these studies have been done on South African individuals, whereas population affinity may influence the parameters. In terms of dental morphology, for example, Pilloud et al[40] showed that external tooth crown measurements varied sufficiently among populations to be used as an additional tool in forensic anthropology for the assessment of ancestry.

The aim of this study is to provide a quantitative analysis of the microstructural anatomy of the first maxillary (MaxFM) and mandibular (MandFM) molar extraction sockets in a South African population. To achieve this objective, critical dento-alveolar parameters characterizing and describing the molar morphology (e.g., tooth width, trunk length, root length, root span) and the corresponding bony socket (e.g., buccal plate thickness, bone density) were assessed on micro-CT scans. We also explored the possible correlation of the various parameters with aging.

Materials and methods

Sample

Thirty-eight modern human skulls (with known age, sex and population affinity) were sourced from the Pretoria Bone Collection (PBC), housed in the Department of Anatomy (University of Pretoria).[41] This collection contains modern skeletal remains of known individuals from South Africa whose bodies have been donated willfully or by local hospitals (i.e., unclaimed bodies). Several population affinities are represented in the collection, with more than half (69%) of the skeletal remains with complete skulls are of African ancestry. Ethics clearance was obtained from the Research Ethics Committee of the Faculty of Health Sciences of the University of Pretoria (Protocol no. 57/2017).

The study sample consisted of adult individuals of African ancestry between 22 and 76 years (mean age: 39.7 years), with thirty males between 24 and 76 years (mean age: 39.5 years) and eight females between 22 and 70 years (mean age: 40.4 years). Individuals were selected according to the following inclusion/exclusion criteria: (1) presence of at least one maxillary and one mandibular first molar; (2) a good state of preservation of the teeth (e.g., no enamel defects and complete roots); (3) no evidence of significant medical or dental history (e.g., sinus pathology, periodontal disease or bone trauma); and (4) absence of metal restorations causing artefacts in imaging acquisitions. Overall, dental and periodontal measurements were performed on 61 teeth: 37 maxillary first molars (MaxFM) and 24 mandibular first molars (MandFM).

Scanning procedure and data collection

The selected specimens were scanned by micro-CT at the South African Nuclear Energy Corporation (Necsa, Pelindaba). The acquisitions were performed with a Nikon XTH 225L industrial CT system (Nikon Metrology, Leuven, Belgium) according to the following parameters: 100 kV voltage, 100 µA current, and 2.00 s exposition time per projection.[32] The final volumes were then reconstructed with an isotropic voxel size ranging from 40 to 48 µm, using Nikon CT Pro software (Nikon Metrology). Subsequently, alignment, measurements and automatic segmentations processes were done with the visualization software VGStudio MAX-3.0 (Heidelberg, Germany).[42] To overcome the introduction of bias, due to oblique planar sections,[43] all the scans were re-oriented following a reference plane commonly used in the literature: the cervical plane, ignoring the occlusal aspect of the crown.[44–47] A set of anatomical landmarks was collected on the 3D model, forming a continuous line along the cementum-enamel junction (CEJ) of the first molar. A best-fit plane (referred then as the cervical plane) was automatically computed through those selected landmarks and was used as a reference to re-align the micro-tomographic image stacks (Figure 1A). Therefore, non-oblique precisely chosen sections (mesiodistal, buccolingual, and occlusal) enabled the assessment of linear measurements, analogous between individuals (Figure 1B-D).

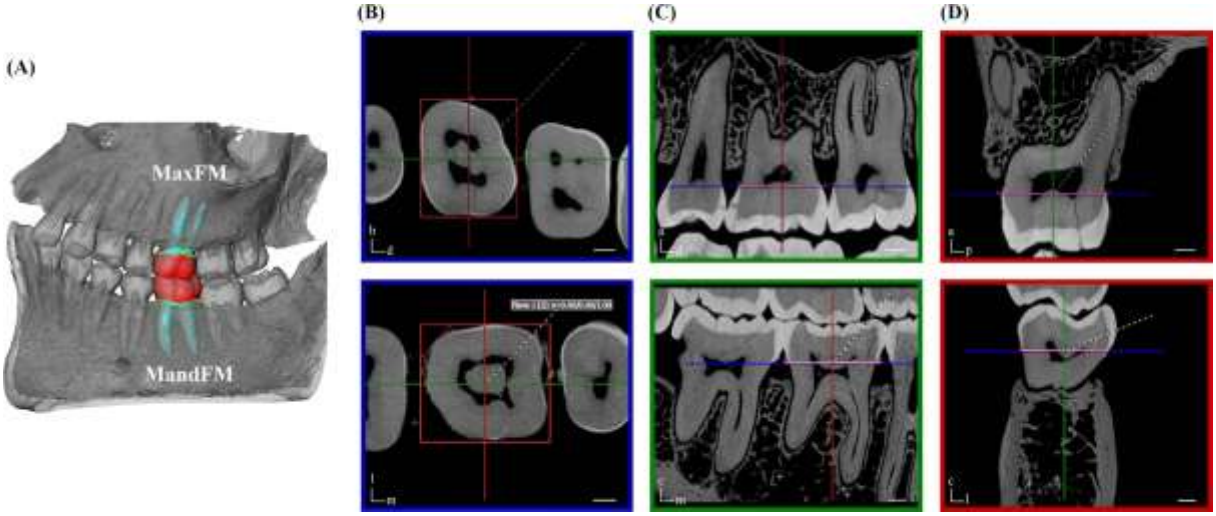

Figure 1. (A) Three-dimensional (3D) model of the maxilla and mandible in semi-transparency (buccal view) with the left first molars virtually rendered (the crown, in red, is delineated from the root, in green, by the best-fitted cervical plane). (B) occlusal, (C) mesiodistal and (D) buccopalatal/lingual sections used to perform the measurements in MaxFM (upper row) and MandFM (lower row). *a*: apical, *b*: buccal, *c*: coronal, *d*: distal, *l*: lingual, *m*: mesial and *p*: palatal. Scale bars: 2 mm

Landmarks, characterizing the external morphology of the first molar, were collected on (1) MaxFM: L_{mb} at mesiobuccal apex, L_{db} at distobuccal apex and L_p at palatal apex; and on (2) MandFM: L_{mb} at mesiobuccal apex, L_{db} at distobuccal apex, L_{ml} at mesiolingual apex (9 of 24 MandFM had a mesiolingual root) and L_{dl} at distolingual apex (2 of 24 MandFM had a distolingual root). Two other landmarks characterizing the surrounding bone were defined, on both MaxFM and MandFM, at the buccal crest (A) and at the deepest point of interradicular bone (I), before the division of the roots from the tooth trunk. Several linear, surface, and volumetric measurements describing the molar morphology and the corresponding bony socket were virtually collected and are detailed in Table 1. The buccal plate thickness (Figure 2A-C) was measured on sections at three different sites: at 1 mm from the buccal crest (b), and adjacent to the buccal roots (b_{mb} at L_{mb}, and b_{db} at L_{db}). Then, three types of tooth widths (Figure 2A, D) were recorded: the minimum width (w) on the mesiodistal section, the mesiodistal (w_{md}) and the buccolingual (w_{bl}) widths at 1 mm from the buccal crest. The following measurements were not assessed on sections but directly on the 3D models (between landmarks), and assisted us in the appreciation of the (1) root length (Figure 2E): distance (I_c) between I and the centroid of the root apex plane, distances between I and each apex, and distances between CEJ and each apex; (2) trunk length: distance I–CEJ; (3) root span or degree of divergence of the roots (Figure 2F, G): distances between each root apex, and calculation of the surface defined by all the root apices.

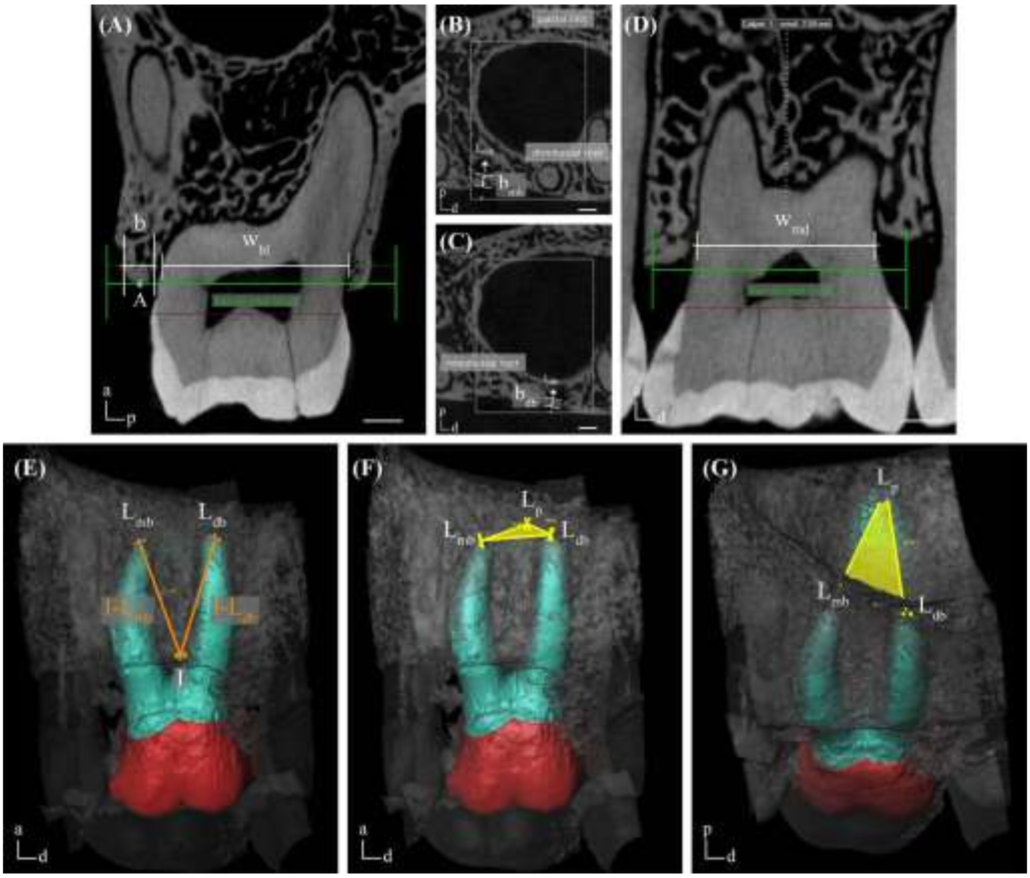

Figure 2. Examples of MaxFM measurements on sections and on the 3D model. Sections: (A) b, and w_{bl}, measured at 1 mm from crest on buccopalatal section, (B) b_{mb}, and (C) b_{db}, on the corresponding occlusal sections, (D) w_{md}, measured at 1 mm from crest on the mesiodistal section. The 3D measurements: (E) root lengths from I shown in orange, (F) and (G) root span dimensions and apex surface drawn in yellow. *A*: buccal bone crest landmark, *I*: deepest landmark of interradicular bone, L_{mb}: mesiobuccal root apex, L_{db}: distobuccal root apex, L_p: palatal root apex, *a*: apical, *d*: distal and *p*: palatal. Scale bars: 2 mm

Table 1. List and descriptions of the variables recorded in MandFM and MaxFM.

	MANDFM	MAXFM
BUCCAL PLATE THICKNESS		
At 1 mm from buccal crest: b	buccolingual section	buccopalatal section
At L_{mb}: b_{mb}	occlusal section	occlusal section
At L_{db}: b_{db},	occlusal section	occlusal section
TOOTH WIDTH		
Minimum width: w	mesiodistal section	mesiodistal section
At 1 mm from buccal crest: w_{md}	mesiodistal section	mesiodistal section
At 1 mm from buccal crest: w_{bl}	buccolingual section	buccopalatal section
ROOT LENGTH		
between I and root apices centroid	I_c	I_c
between I and each root apex	I–L_{mb} / I–L_{db} / I–L_{ml} / I–L_{dl}	I–L_{mb} / I–L_{db} / I–L_p
between CEJ and each root apex	CEJ–L_{mb} / CEJ–L_{db} / CEJ–L_{ml} / CEJ–L_{dl}	CEJ–L_{mb} / CEJ–L_{db} / CEJ–L_p
TRUNK LENGTH		
between I and CEJ	I–CEJ	I–CEJ
ROOT SPAN		
Between each root apex	L_{mb}–L_{db} / L_{mb}–L_{ml} / L_{db}–L_{ml} / L_{db}–L_{dl} / L_{mb}–L_{dl} / L_{ml}–L_{dl}	L_{mb}–L_{db} / L_{mb}–L_p / L_{db}–L_p
Surface defined by all the root apices		
BONE DENSITY		
Cortical BV/TV	buccal plates: I, L_{db}, L_{mb}	palatal plates: I, L_p
Trabecular BV/TV	interradicular bone I	interradicular bone I

I: deepest landmark of interradicular bone, L_{mb}: mesiobuccal root apex, L_{db}: distobuccal root apex, L_{ml}: mesiolingual root apex, L_{dl}: distolingual root apex, L_{ml}: mesiolingual root apex, L_p: palatal root apex, CEJ: cervical plane, BV/TV: bone volumetric fraction.

Bone density in the maxilla and the mandible was also automatically assessed with VGStudioMAX-3.0 software from spherical Volumes of Interest (VOIs) and through histomorphometric parameters such as bone volumetric fraction (BV/TV, %), bone volume (BV, mm^3) and total volume (TV, mm^3). The cortical bone density was evaluated in VOIs located in the palatal plate of MaxFM and in the buccal plate of MandFM. The interradicular trabecular bone density was recorded in both MandFM and MaxFM.

Statistical analysis

Data analysis was performed using the software R v.3.3.2.[48] and statistical significance was accepted at $p < 0.05$. Descriptive statistics, including means and standard deviations (expressed as mean ± SD) were used to have a better understanding of the measurements. Following the results obtained by normality and homoscedasticity tests, differences between measurements and sites were assessed by Kruskal-Wallis analyses, and subsequent pairwise comparisons. To compare the results between maxilla versus mandible, t-tests and/or Kruskal-Wallis analyses were conducted. Spearman's correlation coefficient was also used to study the influence of the age on the variables.

Results

Data from 61 maxillary and mandibular molars were analyzed. The results of the variables assessing the molar morphology are reported in Table 2, the buccal plate thicknesses are detailed in Table 3 and the bone density parameters are in Table 4.

Table 2. Molar morphology variables: tooth width (mm), root length (mm), trunk length (mm), root span (mm) and surface (mm^2) recorded in MandFM and MaxFM.

	MandFM		**MaxFM**	
	min - max	**mean ± SD**	**min - max**	**mean ± SD**
Tooth width				
w	7.88 - 9.55	8.79 ± 0.49	6.11 - 7.94	7.09 ± 0.46
w_{md}	7.13 - 9.57	8.80 ± 0.54	5.47 - 8.56	7.05 ± 0.67
w_{bl}	5.71 - 9.10	7.24 ± 0.96	9.51 - 13.33	11.58 ± 1.08
Root length				
I_c	8.48 - 11.07	9.94 ± 0.85	5.58 - 10.91	8.60 ± 1.27
$I–L_{mb}$	7.40 - 12.18	10.09 ± 1.03	6.26 - 12.37	9.55 ± 1.32
$I–L_{db}$	8.06 - 13.39	10.91 ± 1.05	6.76 - 12.67	9.95 ± 1.38
$I–L_{ml}$ / $I–L_p$	8.60 - 10.70	9.89 ± 0.70	5.35 - 12.26	10.37 ± 1.44
$I–L_{dl}$	8.28 - 10.57	9.43 ± 1.62		
$CEJ–L_{mb}$	12.76 - 15.98	14.36 ± 0.88	10.83 - 15.50	13.50 ± 1.06
$CEJ–L_{db}$	11.84 - 15.74	13.92 ± 1.07	10.57 - 14.92	12.78 ± 1.11
$CEJ–L_{ml}$ / $CEJ–L_p$	13.05 - 15.26	14.06 ± 0.86	11.56 - 16.34	13.74 ± 1.13
$CEJ–L_{dl}$	11.87 - 13.37	12.62 ± 1.06		
Trunk length				
I–CEJ	3.23 - 6.54	4.62 ± 0.67	3.41 - 7.17	5.13 ± 0.74
Root span				
$L_{mb}–L_{db}$	2.16 - 10.57	5.98 ± 1.70	1.65 - 7.52	4.33 ± 1.91
$L_{db}–L_{ml}$ / $L_{db}–L_p$	2.64 - 9.47	6.24 ± 1.86	5.54 - 13.62	10.55 ± 1.74
$L_{mb}–L_{ml}$ / $L_{mb}–L_p$	1.14 - 6.75	3.10 ± 1.34	7.06 - 13.36	10.04 ± 1.49
$L_{db}–L_{dl}$	2.56 - 5.48	4.02 ± 2.06		
$L_{dl}–L_{mb}$	2.67 - 7.68	5.18 ± 3.54		
$L_{dl}–L_{ml}$	1.97 - 5.61	3.79 ± 2.57		
Surface	3.52 - 36.36	10.61 ± 8.93	2.95 - 47.13	21.34 ± 8.84

I: deepest landmark of interradicular bone, L_{mb}: mesiobuccal root apex, L_{db}: distobuccal root apex, L_{ml}: mesiolingual root apex, L_{dl}: distolingual root apex, L_{ml}: mesiolingual root apex, L_p: palatal root apex, CEJ: cervical plane.

Table 3. Buccal plate thicknesses (mm) and frequency distributions (%) in MandFM and MaxFM.

	MandFM			**MaxFM**		
Thickness	**min - max**	**mean ± SD**		**min - max**	**mean ± SD**	
b	0.44 - 3.10	1.46 ± 0.58		0.00 - 2.31	1.00 ± 0.53	
b_{mb}	1.26 - 4.30	2.51 ± 0.94		0.00 - 3.98	0.99 ± 0.98	
b_{db}	1.25 - 5.42	3.29 ± 1.18		0.00 - 3.78	0.99 ± 0.99	
Frequency	**b < 1**	**1 < b < 2**	**b > 2**	**b < 1**	**1 < b < 2**	**b > 2**
b	20.83	66.67	12.50	62.16	35.14	2.70
b_{mb}	0.00	45.83	54.17	56.76	35.14	8.11
b_{db}	0.00	16.67	83.33	66.67	16.67	16.67

Frequencies separated in three groups according to the thickness: < 1 mm, between 1 and 2 mm, and > 2 mm.

Table 4. Cortical and trabecular bone densities (BV/TV, %) in MandFM and MaxFM.

	min - max	**mean ± SD**
MandFM		
Cortical VOIs		
buccal plate - I	0.00 - 99.78	70.28 ± 33.45
buccal plate - L_{db}	93.53 - 99.96	99.44 ± 1.42
buccal plate - L_{mb}	91.01 - 99.95	98.58 ± 2.40
Trabecular VOI		
interradicular - I	19.29 - 75.30	49.74 ± 15.38
MaxFM		
Cortical VOIs		
palatal plate - I	0.00 - 99.65	82.49 ± 33.89
palatal plate - L_p	50.72 - 99.72	92.46 ± 11.97
Trabecular VOI		
interradicular - I	19.06 - 83.25	54.13 ± 14.97

VOIs: Volumes of Interest, BV/TV: bone volumetric fraction, I: deepest landmark of interradicular bone, L_{db}: distobuccal root apex, L_{mb}: mesiobuccal root apex, L_p: palatal root apex.

Molar morphology

The results for the tooth width are summarized in Figure 3 for the mandible and the maxilla. In MandFM and MaxFM, w_{bl} was significantly different from w and w_{md} ($p < 0.01$): w_{bl} was thinner than w and w_{md} in MandFM, whereas it was thicker in MaxFM. The three types of tooth widths were also significantly different between the maxilla and the mandible ($p < 0.01$): w and w_{md} were thicker in MandFM than in MaxFM, while w_{bl} was thinner in MandFM than in MaxFM. As far as root length is concerned, it was found that the distance I_c was significantly greater ($p < 0.01$) in MandFM than in MaxFM (Figure 4A). Significant differences ($p < 0.05$) between MandFM and MaxFM were also reported for the distances between I, or CEJ, and each apex landmark, with greater distances in the mandible. The distance I–CEJ, appreciating the trunk length, was significantly smaller ($p < 0.05$) in MandFM than in MaxFM (Figure 4B). The root span was estimated via the measurement of the distances between all apices and was found to be significantly different ($p < 0.001$) between MandFM and MaxFM. The surface calculated between the apex landmarks confirmed that the spreading of the roots is significantly larger ($p < 0.001$) in MaxFM than in MandFM (Figure 4C). In MaxFM, the surface averaged 21.34 ± 8.84 mm^2, whereas in MandFM, the mean surface was only 10.61 ± 8.93 mm^2.

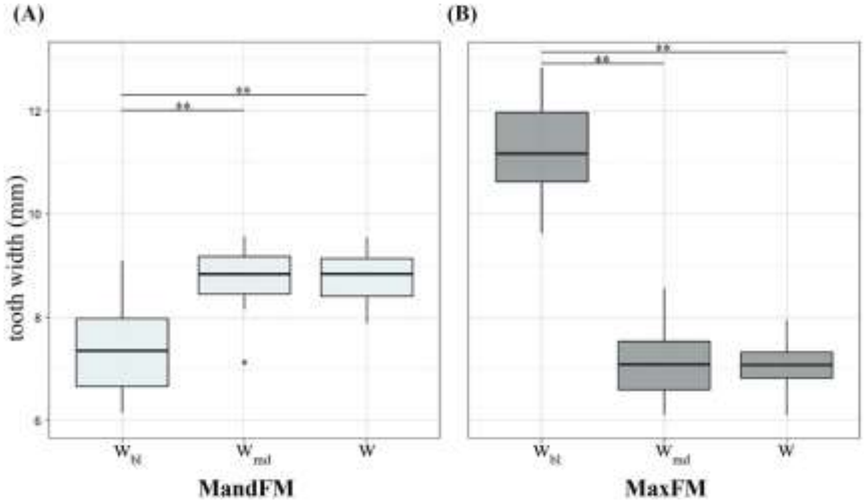

Figure 3. Boxplots of tooth width (mm) in (A) MandFM (light gray) and (B) MaxFM (dark gray), separated by tooth width type (w_{bl}, w_{md}, w). Circles depict outliers, ** $p < 0.01$

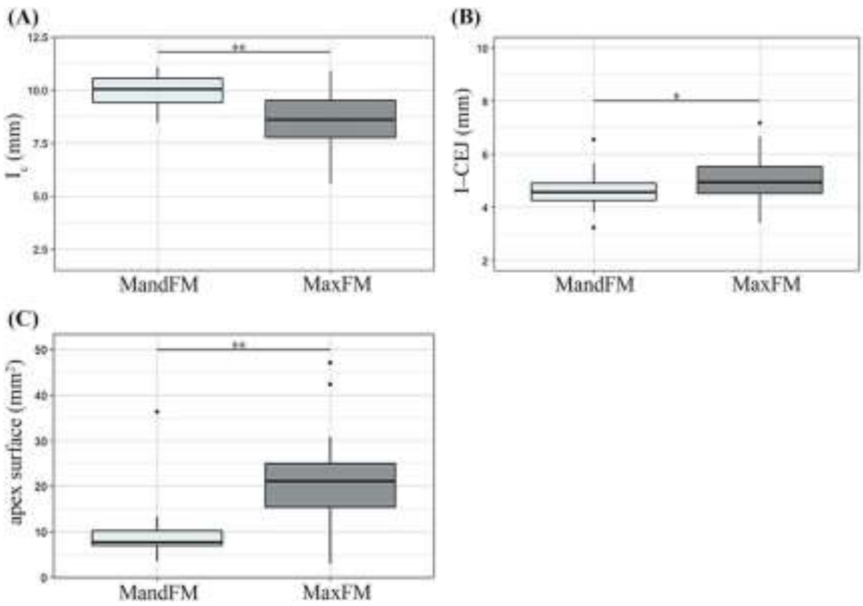

Figure 4. Boxplots of dimensions, performed between landmarks, in MandFM (light gray) and MaxFM (dark gray). (A) I_c (mm) appreciating the root length, (B) I–CEJ (mm) assessing the trunk length, (C) apex surface area (mm^2). Circles depict outliers. ** $p < 0.01$, * $p < 0.05$

Bony socket architecture

The mean maxillary buccal plate thickness (Figure 5A) was less than 1 mm in most of the cases: 62.16% at b, 56.76% at b_{mb} and 66.67% at b_{db}, whereas in the mandible (Figure 5B), only 20.83% of the individuals at b, and none at both apices were less than 1 mm. Furthermore, 83.33% (at distobuccal apex) and 54.17% (at mesiobuccal apex) of the MandFM buccal plates were thicker than 2 mm, while at MaxFM, only 16.67% and 8.11% were thicker, respectively. No significant differences between the sites (b, b_{mb} and b_{db}) were reported at MaxFM while the three sites were all significantly different ($p < 0.01$) from each other at MandFM. Significant differences ($p < 0.01$) were also found between the maxillary and mandibular buccal plate thicknesses, with a constantly thicker MandFM buccal plate at all sites.

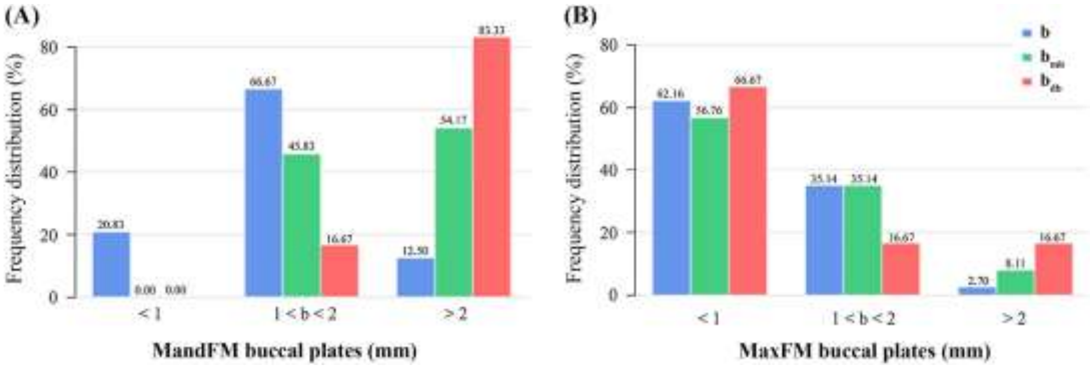

Figure 5. Frequency distribution of buccal plate thickness (mm) in (A) MandFM and (B) MaxFM. Frequencies classified by buccal plate type (b in blue, b_{mb} in green, b_{db} in red) and separated in three groups according to the thickness: < 1 mm, between 1 and 2 mm and > 2 mm.

Cortical and trabecular bone density were assessed in the maxilla and the mandible by histomorphometric parameters. In MandFM, a wide range of bone densities was observed in the trabecular and cortical bones (Figure 6A). In the interradicular VOI, the BV/TV ranged from 19.29% to 75.30%, whereas in the buccal cortical bone (at I level), the range was from 0% (absence of buccal plate) to 99.78%. Mean cortical bone density at the buccal plates of the apices were 98.58% at L_{mb} and 99.44% at L_{db}. All sites (cortical or trabecular) were statistically significantly different from each other ($p < 0.001$) for these parameters. Regarding MaxFM (Figure 6B), the BV/TV ranged from 19.06% to 83.25% in the interradicular trabecular bone, whereas in the palatal cortical bone (at I level), the range was from 0% (absence of buccal plate) to 99.65%. Mean cortical bone density of the palatal plate (at L_p level) was 92.46%. The bone density differed significantly between trabecular and cortical sites ($p < 0.001$), but no differences were detected between the two maxillary cortical sites. The comparison between MandFM and MaxFM interradicular trabecular densities did not show a significant difference.

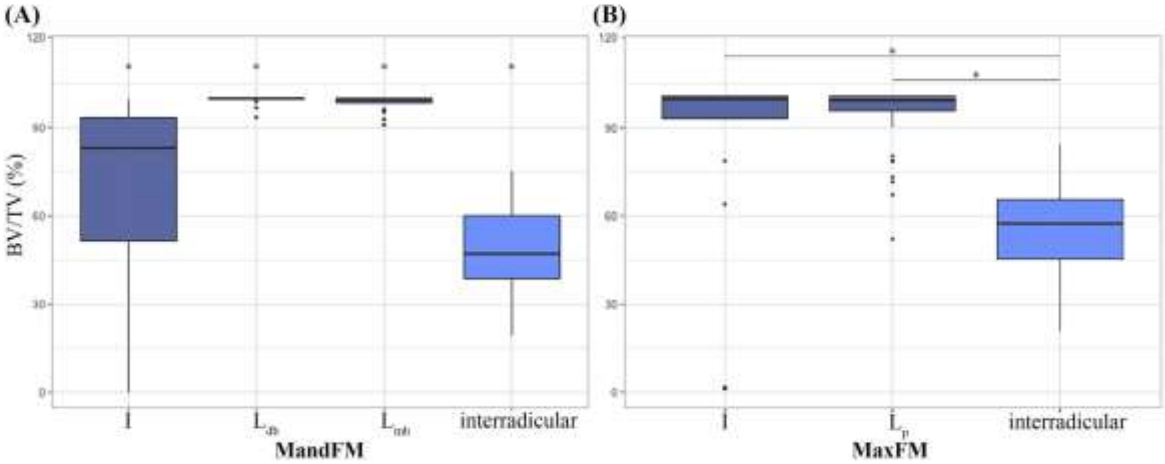

Figure 6. Boxplots of (A) mandibular and (B) maxillary BV/TV (%) separated by VOI site (I, L_{db}, L_{mb}, L_p, interradicular) and according to bone type (cortical density in dark blue, trabecular density in light blue). Circles depict outliers, * $p < 0.001$.

Correlation with aging

Correlations between each variable (tooth width, root length, trunk length, root span, buccal plate thickness and bone density) and aging were assessed. Only bone density showed significant correlations with age. A significant decrease ($p < 0.05$) was found in MandFM between age and cortical bone density of the buccal plate at I level (Figure 7A). In MaxFM, significant decreases ($p < 0.001$) with aging were also found in the two cortical sites (Figure 7B, C), but not in the trabecular site.

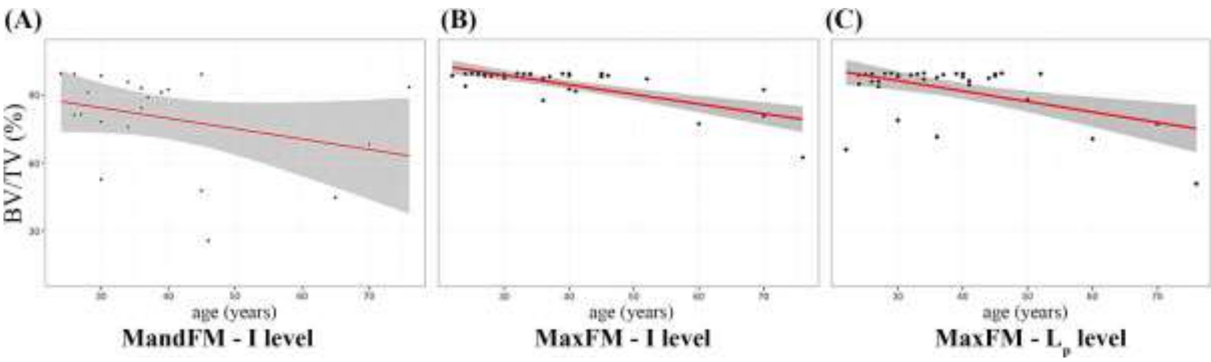

Figure 7. Linear regressions of BV/TV (%) with age. (A) at I, in the mandibular buccal cortical bone, (B) at I, in the maxilla, and (C) L_p, in the maxillary palatal cortical bone.

Comparison with buccal plate

Relationships between the buccal plate thickness and the other measurements (tooth width, root length, trunk length, root span and bone density) were also investigated, but no significant correlations were detected.

Discussion

To the best of our knowledge, this is the first micro-CT-based study exploring the anatomy of human first molar sockets at this level of detail, and more particularly, for dental implant related purposes. As a gold standard modality for bone microstructure assessment, micro-CT offers quantitative and objective parameters. Our research provides anatomical measurements at dental implant sites, including minimum, maximum and mean distances, characterizing the first molars (e.g., tooth width, trunk length, root length and root span) and their intact extraction sockets (e.g., buccal plate thickness and bone density).

The external shape and outline of the tooth are the main features in defining the three-dimensional bony structure of the socket. Variables assessing the tooth width, the trunk length, the root length and the root span are relevant in estimating parameters of the implant design, as well as the height, depth and width of bone available for safe implant placement.[13] However, to date, few studies have performed similar measurements (Table 5). For example, Smith and Tarnow[13] assembled from the literature[4,49] anatomical dimensions, such as tooth width, root and trunk lengths, serving as a basis for many statements in dentistry, but our findings were found to be smaller than those of previous studies. These differences could possibly be explained by the differences in the techniques used. For instance, Kerns et al[49] performed their measurements on extracted teeth with calipers while our study used dimensions performed on embedded teeth micro-CT-scanned in their bony sockets. Nevertheless, we could confirm some general trends, for example, the trunk length is shorter in mandibular first molars than in maxillary molars caused by a closer distance between the root furcation and the CEJ. Matsuda et al[24] measured the distances between the apices on CBCT scans to assess the spreading of the roots or the degree of divergence of the roots – equivalent to the root span in our study. They stated that for the stability of the implant, more than 5 mm is necessary. For this reason, all of our sites could be considered adequate as the minimum distances between the mandibular or maxillary apices were systematically greater than 5 mm.

The buccal plate thickness is known to be one of the most important measurements when it comes to dental implant survival and success.[14,16,21,24,50] If the buccal plate is absent, an immediate implant placement is precarious due to a higher risk for poor stability and a reduced potential for bone fill on the buccal side of the implant as well as implant thread exposure in the long-term. Previous findings[5,24,50] stated that sites with thick bony walls (> 1 mm) usually had better bone fill after immediate implantation compared to sites with a thin plate. In the mandible, only 20.83% of the sites showed a buccal plate thickness of less than 1 mm. However, in the maxilla, we found that at 1 mm from crest, 62.16% of the MaxFM sites had a buccal plate thinner than 1 mm, and only 2.7% of the plates were thicker than 2 mm. Huynh-Ba et al[14] also found thin buccal walls (< 1 mm) in the majority of their maxillary extraction sites. In contrast to our findings and using CBCT, Matsuda et al[24] showed that 92% of maxillary first molars sites had a buccal plate thickness greater than 1 mm, and that 20% of the sites were thicker than

Table 5. Characteristics of selected studies. Buccal plate thicknesses and molar morphology variables are in mm, trabecular bone densities are in %. (NA: variable not available or not recorded in the study).

		Sample					**min-max**		**mean ± SD**	
Study		**Type (tooth)**	**N**	**Age (mean)**	**Modality**		**maxilla**	**mandible**	**maxilla**	**mandible**
						Buccal plate				
Huynh-Ba et al.[14]	2010	Patient (PM)	93	NA	Caliper	At 1 mm from crest	0.5 - 3.0	NA	1.1 ± 0.50	NA
Jung & Cho[19]	2012	Patient (M1)	83	20 - 53 (28.8)	CBCT	At apex, mesial root	NA	NA	1.23 ± 0.96	NA
						At apex, distal root	NA	NA	1.91 ± 1.18	NA
Kang et al.[21]	2015	Patient (M1)	132	21 - 59 (31)	CBCT	At apex, mesial root	NA	NA	3.00 ± 1.57	NA
						At apex, distal root	NA	NA	3.13 ± 1.48	NA
Temple et al.[16]	2015	Patient (M1)	265	20 - 85 (55.9)	CBCT	At 1 mm from crest, mesial root	0.19 - 2.26	0.11 - 3.31	0.914	0.587
						At 1 mm from crest, distal root	0.40 - 2.81	0.27 - 4.37	1.262	0.673
Matsuda et al.[24]	2016	Patient (M1)	95	18 - 76 (37.2)	CBCT	At 2 mm from crest	NA	NA	1.58 ± 0.6	NA
						Molar morphology				
Smith and Tarnow[13]	2013	Extracted teeth (M1)	NA	NA	Caliper	Mesiodistal tooth width at CEJ	9.20	NA	7.90	NA
						Buccolingual tooth width at CEJ	9.00	NA	10.70	NA
						Root length	13.50	NA	13.00	NA
						Trunk length	3.27	NA	4.10	NA
						Bone Density (BV/TV)				
Akça et al.[38]	2006	Cadaver	1	NA	Micro-CT	Biopsies of trabecular bone in edentulous sites	NA	NA	26.95	69.95
De Oliveira et al.[15]	2012	Patient	32	25 - 67 (42)	Micro-CT	36 biopsies of trabecular bone in edentulous sites	11.1 - 67.9		35.5 ± 14.3	
González-Garcia & Monje[30]	2013	Patient	31	20 - 79 (51.6)	Micro-CT	39 biopsies of trabecular bone in edentulous sites	13.22 - 72.99		48.7 ± 17.85	
Kim & Henkin[17]	2015	Cadaver	12	NA	Micro-CT	34 biopsies of trabecular bone in edentulous sites	2.4 - 48.2		14.59 ± 7.68	27.28 ± 10.19
Parsa et al.[31]	2015	Cadaver	20	NA	Micro-CT	Trabecular VOIs in edentulous sites	NA	2.24 - 75.83	NA	32.35 ± 18.81

PM and M1: pre-molars and first molars, CEJ: cervical plane, VOIs: Volumes of Interest.

2 mm. Temple et al[16] measured buccal thicknesses on CBCT scans of maxillary and mandibular first molars, and their results were found to be slightly smaller than reported in our study. However, some trends are similar, for example, the mandibular buccal plate adjacent to the mesial root apex is thinner than in the distal root. Thus, the mandibular sites, with a greater thickness compared to the maxillary sites, may allow more predictable outcomes for immediate implant placement. The limited and non-significant effect of aging on the buccal wall, confirmed by this study, was also demonstrated by Temple et al.[16] The main difference between the maxilla and the mandible in our study was partly a reflection of fenestrations or dehiscences at the mesiobuccal and distobuccal apices of a few maxillary molars with no buccal plate at all, while fenestrations were absent in the mandible. Although minor fenestrations may not have a negative impact on implant placement or success, it is worthwhile to know that they are likely to occur, and if they are of significant dimensions, one may need to consider an alternative treatment protocol. This could include a simultaneous augmentation or a delayed placement protocol.

Histomorphometric parameters, evaluated in various locations of the periodontal and alveolar bones, give a quantitative and objective insight into the microstructural anatomy of the maxillary and mandibular sockets.[15,17,30,33] Kim & Henkin[17] in a micro-CT based study on biopsies from maxillae and mandibles of 12 cadaver specimens, obtained a mean trabecular BV/TV of 14.59% and a range from 2.4% to 48.2%. Their values were lower than what we could observe, with a mean BV/TV of 54.13% in the maxilla and 49.74% in the mandible. Other micro-CT-based studies[15,30] however, obtained values approximating ours: De Oliveira et al[15] had a mean BV/TV of 35.5% (range: 11.1 – 67.9%) and González-Garcia & Monje[30] had a mean BV/TV of 48.70% (range: 13.22 – 72.99%). Nevertheless, none of these studies measured the density in the interradicular bone, but in a different location of the alveolar bone. Higher values observed in our study might reflect variations in trabecular density between sites, with a denser interradicular bone than in the rest of the trabecular bone. This variation could be an indication of the specific mechanical competence of the interradicular bone in tooth retention. In our sample, we also noticed that the mandibular and the maxillary trabecular bones had similar densities, while the cortical bone densities were higher in the mandible than in the maxilla. Similar results have been observed previously.[30,51] The cortical as well as the trabecular bone density influence the primary stability of an implant, the anchorage and therefore the success of the implantation.[18,38,52] Aranyarachkul et al[52] stated that the clinical success of implants is influenced by the bone quality and density of the implantation site. Furthermore, as bone density varies from site to site, and from patient to patient, several previous studies[15,30,39,52,53] recommend performing a bone density evaluation using CBCT prior to implant placement. The age of the patient is also of major importance as we found that the cortical bone densities of the buccal and palatal/lingual plates were decreasing with advancing age.

In the present study, we obtained three-dimensional dental and periodontal measurements describing and quantifying the morphology and the microstructure of the first maxillary and mandibular molars and sockets in South African skulls. These population-based reference values, and their correlation with advancing age, may be of great importance for the use of immediate implant placement in molar extraction sockets and thus the potential long-term success of this treatment modality. They also may enable the optimization of the implant design with more precise and specific constraints in order to obtain the best and optimal fit within the multi-rooted socket. The variables assessed are relevant in estimating parameters of the implant design and position, such as the width of the implant platform, the body shape and taper of the implant.

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