Original Article

The Validity of In Vivo Tooth Volume Determinations From Cone-Beam Computed Tomography

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ABSTRACT

Objective: To determine the accuracy of volumetric analysis of teeth in vivo using cone-beam computed tomography (CBCT).

Materials and Methods: The physical volume (Vw) of 24 bicuspids extracted for orthodontic purposes (16 were imaged with the I-CAT and 8 with the CB MercuRay) were determined using the water displacement technique. Corresponding pretreatment CBCT image data were uploaded into Amira 4.0 for segmentation and radiographic volume (Va). All measurements were performed twice by two observers. The statistical difference between Vw and Va was assessed using a paired *t*-test. The intraobserver and interobserver reliability were determined by calculating Pearson correlation coefficients and intraclass correlation coefficients.

Results: The overall mean Vw of teeth specimens was 0.553 ± 0.082 cm^3, while the overall mean Va was 0.548 ± 0.079 cm^3 (0.529 ± 0.078 cm^3 for observer 1 and 0.567 ± 0.085 cm^3 for observer 2). There were statistically significant differences between Va and Vw ($P < .05$). Between observer 1 and observer 2, Va measurements were statistically significantly different ($P < .05$). The interobserver and intraobserver correlation coefficient for Vw was high. Lastly, surface smoothing reduced the volume by 3% to 12%.

Conclusions: In vivo determination of tooth volumes from CBCT data is feasible. The measurements slightly deviate from the physical volumes within −4% to 7%. Smoothing operations reduce volume measurements. Currently, no requirements for accuracy of volumetric determinations of tooth volume have been established. (*Angle Orthod.* 2010;80:160–166.)

KEY WORDS: Tooth volume; Cone-beam CT; Segmentation; Radiographic; Orthodontic

INTRODUCTION

Determination of dental root morphology and volume is of great interest to clinical dentistry and orthodontics for biomechanical considerations. With the recent introduction of volumetric imaging via cone-beam computed tomography (CBCT) in dentistry, in vivo three-dimensional (3D) anatomical structure information is available for measurement and analysis.[1] The virtual modeling and development of a 3D setup that displays individual crowns and roots and craniofacial structures would greatly help the clinician in diagnosis and treatment planning to determine various treatment options, monitor changes over time, predict and display final treatment results, and measure treatment outcomes accurately.[2] The accurate virtual model can also be used for bracket positioning,[3,4] especially for lingual appliances,[5] wire bending, and surgical simulation.[6,7] Segmentation of anatomic structures from imaging data is common in medical modeling. The accuracy of bone segmentation has been studied extensively by multislice computed tomography (MSCT)[8–10] and more recently by CBCT.[11,12] However, these CBCT studies are based on a CBCT with a small field of view (FOV),[13,14] which has relatively high contrast image compared with larger FOV CBCT typically used

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Accepted: March 2009. Submitted: December 2008.

DOI: 10.2319/121608-639.1

in orthodontics. While segmentation of teeth has been studied using MSCT,[2] there has been no validation of the accuracy and no published studies using CBCT.

Segmentation of teeth from CBCT allows for virtual modeling of the entire dentition, revealing the root anatomy and the supporting bone, resulting in a more comprehensive model compared with traditional plaster models.[15] This comprehensive 3D model can be integrated and related to the craniofacial volume and contain invaluable information for the clinician to diagnosis, treatment plan, construct individual appliances, and evaluate treatment results.[12]

Management of anchorage is fundamental to the biomechanics of tooth movement. Root surface area is significant in orthodontics as it relates to treatment duration, amount of force required,[16,17] and relative movement of the anterior versus the posterior segment of teeth in cases involving space closure.[18] Similarly, in prosthodontics, periodontics, and endodontics, the amount of root surface area is significant in treatment decisions.[1]

Orthodontic biomechanics are based on tooth anatomy in three dimensions.[19] As CBCT imaging becomes mainstream in orthodontics, for the first time data will be available for the determination of an individual tooth root anatomy and related root surface area. However, to achieve progress toward this goal, it is important that the geometric accuracy of the tooth models is studied. In the approach presented in this article, we assessed the segmentation of teeth models and subsequent volumetric determinations derived from CBCT compared with physical volumes. Differences between direct segmentation and smoothed geometric models were also evaluated.

MATERIALS AND METHODS

This pilot study consisted of samples of 24 extracted teeth (14 upper bicuspids and 10 lower bicuspids) from 9 orthodontic patients, ranging from 14 to 30 years of age with ethnicity and sex composition of 2 white males and 7 white females. All teeth included in the study were extracted as part of a prescribed orthodontic treatment plan. All teeth were brushed under running water to remove adherent blood and cleaned of residual bone, soft tissue, and calculus.

Patients (n = 7, with 16 teeth studied) were imaged with the I-CAT (Imaging Sciences International, Hatfield, Penn) using the 16 × 13 cm (diameter × height) FOV. Other patients (n = 2, with 8 teeth studied) were imaged with the Hitachi MercuRay Cone Beam CT device (Hitachi Medical Corp, Twinsburg, Ohio) using the 15-cm FOV. The scans were taken as recommended by the manufacturer's patient positioning protocol reference manual. The isotropic voxel size was 0.292 mm (120 kV, 10 mA) for CB MercuRay and 0.25 mm, 0.30 mm (120 kV, 18 mA), and 0.40 mm (120 kV, 24 mA) for I-CAT in three different settings. All data sets were exported using the Digital Imaging and Communication in Medicine (DICOM) version 3 format file with the same slice distance as the voxel size.

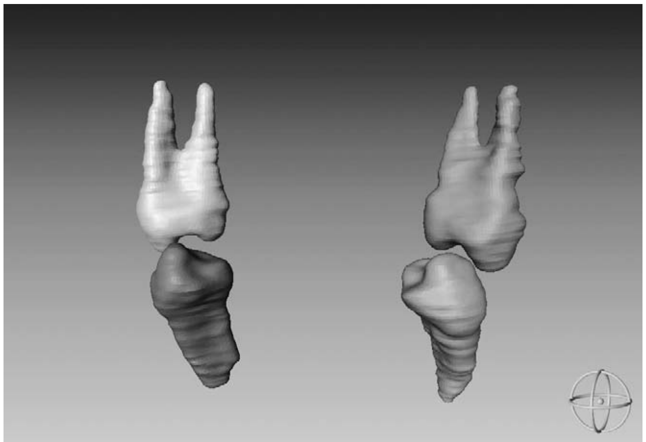

Figure 1. Teeth segmentation in Amira.

Tooth Physical Volume Measurements

Tooth physical volume (Vw) was determined by the water displacement method[20,21] in a 10-mL graduated cylinder with gradations of 0.1 mL (Fisher Scientific, Pittsburgh, Penn). The cylinder was filled with water at room temperature (23.5°C) to the 9-mL mark. The tooth was then completely immersed in the cylinder, and the new water level was recorded. The reading was at the lowest portion of the meniscus. The volume of the displaced water was then obtained by subtracting the initial water volume from the final volume obtained after immersing the tooth in the water.[22,23] To reduce measurement errors, the volume of each tooth was measured twice as described above by two independent observers.

Tooth Segmentation

Amira 4.0 (Visage Imaging Inc, Carlsbad, Calif) was used for tooth segmentation (Figure 1). Segmentation was performed on consecutive 2D slices using the magic wand as the region-growing tool. This tool selects the largest connected area that contains all voxels, with gray values lying inside a user-defined range. The range can be specified within a selected grayscale range. These values can be selected to define absolute gray values or values relative to the gray value of the seed pixel. Segmentation is semiautomated with manual intervention. All teeth were segmented twice by two independent observers. Each tooth in the same DICOM volumetric data was color coded to fa-

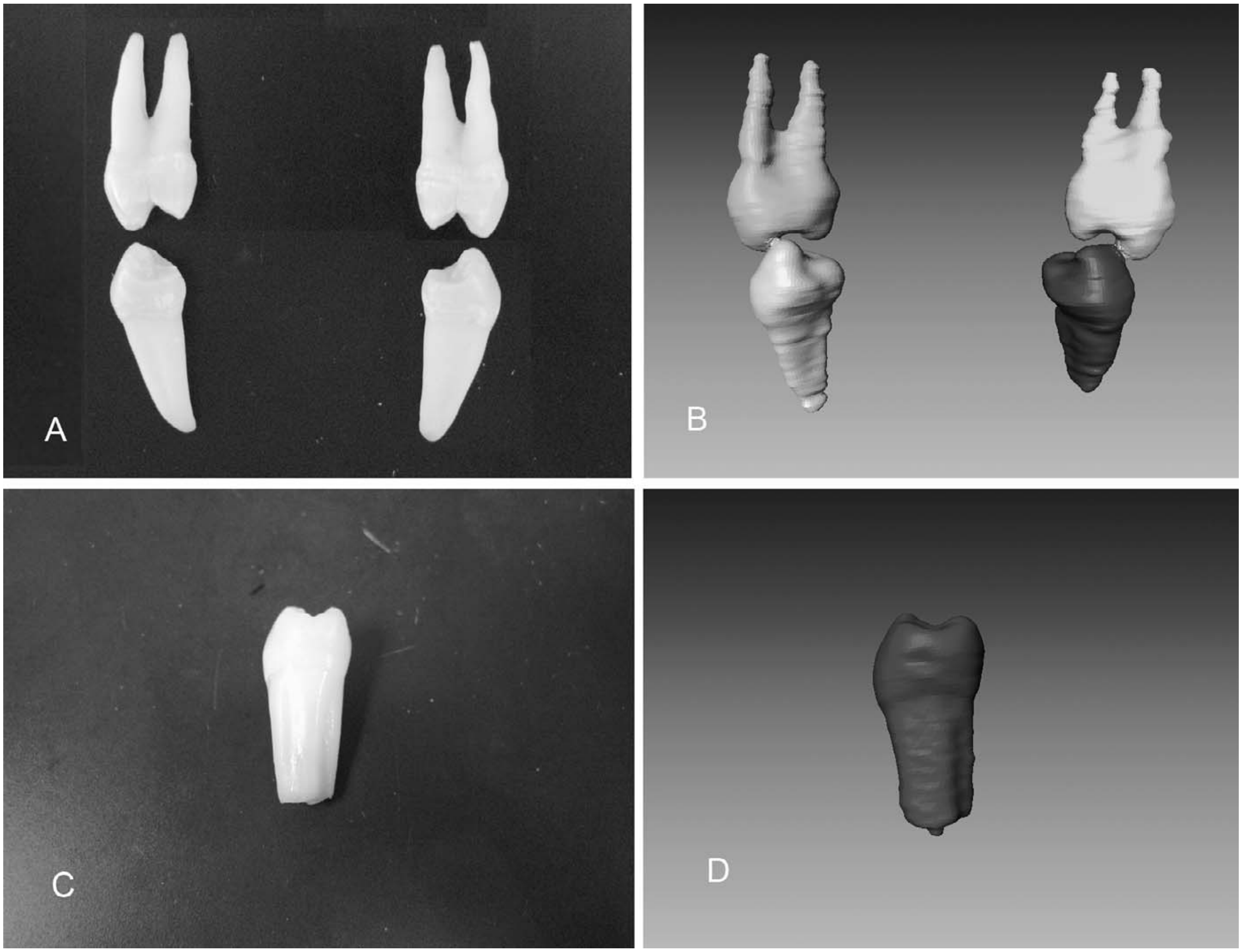

Figure 2. Virtual segmented teeth compared with physical teeth. (A) Physical four bicuspids, two roots for upper bicuspids. (B) Four bicuspids segmented from cone-beam computed tomography data sets. (C) Lower bicuspid with developing apex. (D) Apex can be seen clearly in segmented tooth.

cilitate differentiation (Figure 2A–D). After segmentation, the software automatically computed each tooth's radiographic volume (Va) from the stack of segmented 2D slices. A smoothing function was used after the calculation of segmentation, and the corresponding volume (Vs) after smoothing was also recorded (Figure 3A–D).

Data Statistical Analysis

All data were entered into Excel 2003 (Microsoft, Redmond, Wash). The statistical analyses were carried out with SPSS (Version 12.0, SPSS, Chicago, Ill). Pearson correlation coefficients were performed to determine the reliability between the first and second measurements of two observers. An intraclass correlation coefficient (ICC; a two-way mixed effect model) was then calculated on the recorded measurements to determine the level of interobserver reliability. Accuracy of the CBCT volume measurements was assessed by comparison with the direct volume measurement of the same tooth using the paired Student's *t*-test. The level of significance was set at 5% ($P < .05$).

RESULTS

The teeth physical volume (cm^3; Vw) and the radiographic volume measurements (Va) are presented in Table 1. The mean physical tooth volume (Vw) was 0.554 ± 0.082 cm^3. The mean radiographic volume (Va), as obtained by CBCT imaging, was 0.529 ± 0.078 cm^3 for observer 1 (the mean difference is -0.024 ± 0.02 cm^3, $-4.13\% \pm 3.15\%$ compared with Vw), and 0.567 ± 0.085 cm^3 for observer 2 (the mean difference is 0.139 ± 0.037 cm^3, 2.65% ± 6.74% compared with Vw), respectively (overall mean was 0.548 ± 0.079 cm^3).

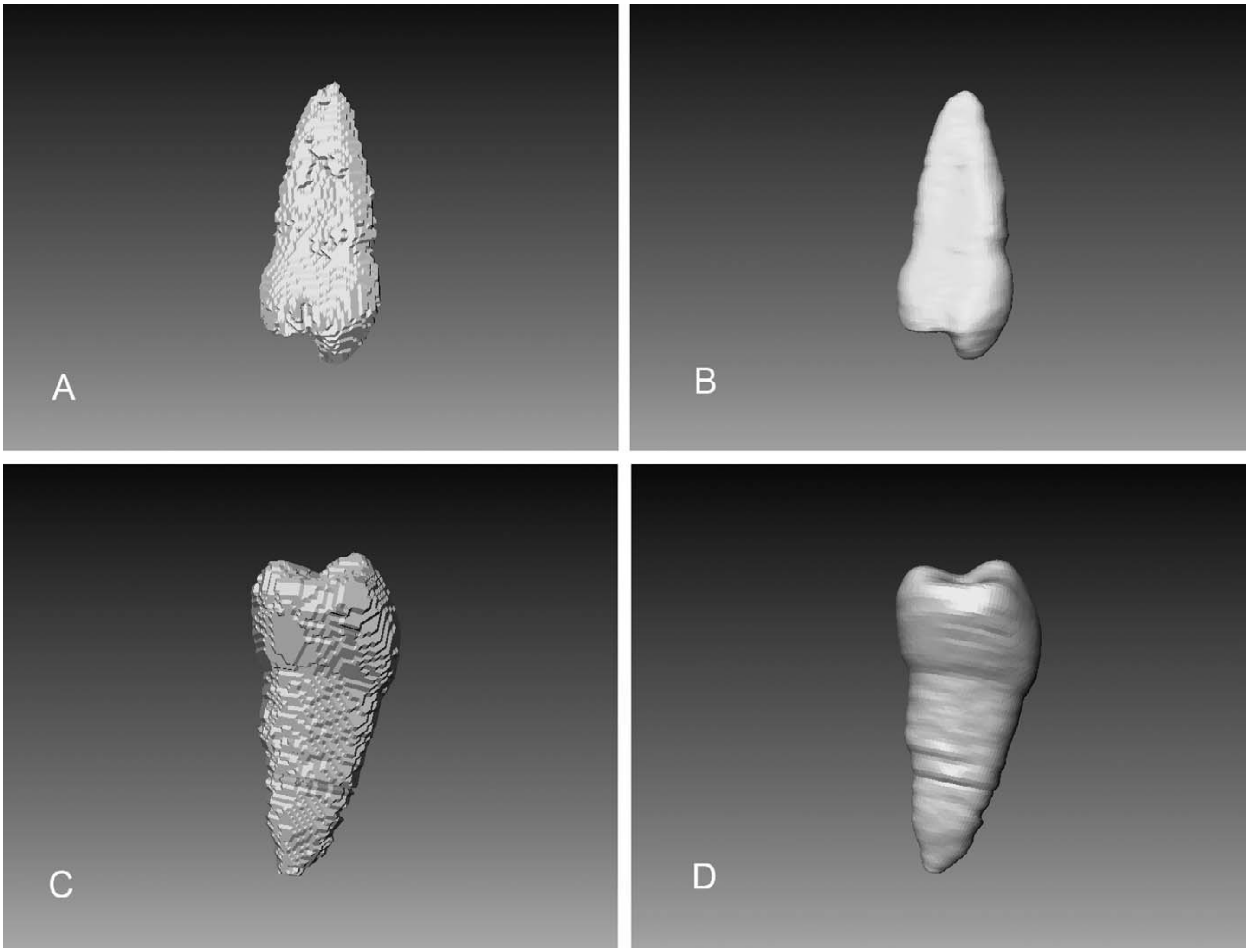

Figure 3. Virtual teeth before and after smoothing. Upper bicuspid virtual model (A) before and (B) after smoothing. Lower bicuspid (C) before and (D) after smoothing.

The mean Va of each observers and Vw were compared to determine the accuracy of segmentation. There was a statistically significant difference between the radiographic volume (Va) and the physical volume (Vw; $P < .05$) and also between the two observers for Va ($P < .05$). Surface smoothing in Amira software made the geometry smaller, by 3% to 12% (6.72% ± 2.60% on average; Table 2).

Intraobserver correlation of both volume measurements by the same observer was high. For the physical tooth volume (Vw), Pearson correlation coefficients were .937 and .939 for the two observers. For the volume derived from segmentation (Va), the intraobserver Pearson correlation coefficients were .943 and .916 for the two observers, respectively.

ICCs (two-way mixed effect model) were calculated on recorded measurements of both investigators, to determine the level of interobserver reliability. For Vw measurement, ICC (interobserver reliability) was .957 and .862 for Va measurement.

DISCUSSION

For the first time, segmentation and in vivo volumetric determinations of teeth from CBCT were performed and compared with physical measurements. While teeth segmentation has been reported from medical CT, there are no studies on the validity of the process.[2] The reported accuracy of bone segmentation varies, and small FOV CBCT devices have been studied. However, these devices generally offer greater image contrast[13,14] compared with the larger FOV CBCT devices typically used in orthodontics, which have relatively lower contrast and a lower signal-to-noise ratio, creating a challenging situation for image segmentation.

The purpose of this pilot study was to test the ac-

Table 1. Comparison of Physical Volume With the Radiographic Volume Measurements of Two Observers[a]

Tooth ID	Mean Vw	Observer 1 Mean			Observer 2 Mean		
		Va	Diff.	%	Va	Diff.	%
1	0.633	0.628	–0.004	–0.67	0.640	0.007	1.18
2	0.605	0.605	0.000	0.07	0.574	–0.031	–5.12
3	0.673	0.626	–0.047	–6.94	0.691	0.018	2.71
4	0.665	0.613	–0.052	–7.84	0.695	0.030	4.58
5	0.518	0.487	–0.030	–5.86	0.569	0.052	9.95
6	0.498	0.477	–0.020	–4.09	0.580	0.083	16.67
7	0.575	0.550	–0.025	–4.29	0.572	–0.003	–0.48
8	0.488	0.448	–0.040	–8.12	0.521	0.033	6.82
9	0.460	0.433	–0.028	–5.98	0.407	–0.053	–11.51
10	0.443	0.408	–0.035	–7.82	0.420	–0.023	–5.12
11	0.688	0.652	–0.035	–5.16	0.654	–0.034	–4.95
12	0.663	0.618	–0.045	–6.78	0.601	–0.061	–9.25
13	0.500	0.480	–0.020	–4.06	0.526	0.026	5.29
14	0.493	0.466	–0.027	–5.43	0.504	0.012	2.42
15	0.498	0.454	–0.043	–8.68	0.543	0.045	9.06
16	0.463	0.428	–0.034	–7.44	0.468	0.005	1.12
17	0.610	0.623	0.013	2.14	0.644	0.034	5.64
18	0.593	0.588	–0.004	–0.73	0.574	–0.019	–3.13
19	0.530	0.517	–0.013	–2.42	0.555	0.025	4.66
20	0.540	0.527	–0.013	–2.40	0.574	0.034	6.27
21	0.450	0.448	–0.002	–0.50	0.458	0.008	1.77
22	0.445	0.464	0.019	4.18	0.470	0.025	5.71
23	0.635	0.582	–0.054	–8.43	0.718	0.083	13.04
24	0.600	0.563	–0.038	–6.25	0.638	0.038	6.36

[a] Vw indicates the mean physical volume by water displacement method; Va, the mean radiographic volume derived from Amira for each observer.

Table 2. The Change of Teeth Volume After Smoothing[a]

Tooth ID	Observer LY		Diff.	%	Observer 2 RO		Diff.	%
	Va1	Vs1			Va2	Vs2		
1	0.627	0.595	0.032	5.12	0.640	0.606	0.034	5.30
2	0.603	0.571	0.032	5.32	0.574	0.543	0.031	5.37
3	0.602	0.568	0.034	5.65	0.703	0.666	0.036	5.18
4	0.603	0.566	0.037	6.12	0.717	0.674	0.043	6.05
5	0.493	0.459	0.034	6.91	0.605	0.568	0.036	6.00
6	0.507	0.473	0.033	6.57	0.580	0.548	0.032	5.59
7	0.539	0.511	0.027	5.05	0.572	0.542	0.030	5.26
8	0.449	0.423	0.026	5.77	0.670	0.638	0.032	4.78
9	0.417	0.396	0.022	5.22	0.445	0.422	0.023	5.14
10	0.407	0.387	0.021	5.13	0.443	0.420	0.023	5.15
11	0.629	0.609	0.021	3.27	0.672	0.649	0.024	3.53
12	*0.598*	0.577	0.022	3.61	0.608	0.584	0.024	3.90
13	0.465	0.437	0.029	6.19	0.534	0.503	0.031	5.86
14	*0.468*	0.445	0.023	4.96	0.518	0.488	0.030	5.74
15	0.453	0.425	0.028	6.13	0.573	0.543	0.030	5.18
16	0.432	0.406	0.027	6.15	0.484	0.456	0.029	5.93
17	0.616	0.572	0.045	7.25	0.638	0.589	0.048	7.59
18	0.565	0.525	0.041	7.20	0.583	0.538	0.045	7.74
19	0.491	0.460	0.032	6.41	0.565	0.531	0.034	6.05
20	0.523	0.494	0.030	5.68	0.570	0.536	0.034	5.97
21	0.452	0.396	0.056	12.47	0.458	0.399	0.059	12.83
22	0.446	0.390	0.057	12.68	0.470	0.411	0.059	12.54
23	0.600	0.524	0.076	12.71	0.696	0.618	0.078	11.24
24	0.575	0.511	0.065	11.26	0.623	0.557	0.066	10.55

[a] Vs is smoothed volume from Amira.

curacy of volume measurements derived from CBCT images. We found that the difference between the physical volume measured of extracted teeth was statistically significant different from those obtained from the CBCT images ($P < .05$). The two observers showed different tendencies with the volumetric measurements from CBCT: observer 1's results were generally smaller than the physical volume and observer 2's measurements were generally larger than the physical volume. This suggests that the subjective aspects of segmentation can affect the volumetric measurements. However, this difference was limited to $-4.13\% \pm 3.15\%$ and $2.65\% \pm 6.74\%$ difference for observer 1 and 2, respectively. Because these differences are relatively small, the clinical significance of these findings is not established. A common use of segmented tooth models in orthodontics is to conduct various study model analysis, such as arch length discrepancy and Bolton analysis. These data suggest that the differences in segmentation are relatively small and would not likely influence common study model analysis for diagnosis and treatment planning.

There are many factors that could affect the accuracy of segmentation. Image quality is predominant for segmentation. CBCT imaging quality can be related to machine settings, patient positioning and management, volume reconstruction, and DICOM export. In this study, data sets were from two different CBCT machines performed in different settings. This heterogeneity could contribute to different image intensities and influence the segmentation result. All data sets from CBCT were reconstructed and exported into DICOM format, a function that varies between different machines.

Since our study was based on archival data of humans, motion-related artifacts could also influence the accuracy of segmentation. CBCT for orthodontics is typically performed in approximately 20 seconds, and during the process, any movement of the patients will affect the quality of the final image. Movement artifacts may be considerable in younger patients who have more difficulty keeping still.

There is no standard method approach or methodology to segmentation. Segmentation is largely based on imaging thresholding. The use of a global threshold value for the entire object has the advantage that only a single segmentation parameter is estimated. This is relatively simple and often used for bone segmentation, which commonly has a uniform density throughout the same bone.[24,25] However, the density of teeth is very different from crown to apex, as the contrast between the root and bone decreases. If a single parameter was applied for segmentation, it would not be possible to visualize the crown and root apex at the same time. Therefore, tooth segmentation would require more than one threshold level. In this study, we found that the threshold level needed to be adjusted at least three times as the tissue density and image from crown to apex are significantly different. Two observers segmented teeth subjectively, and although their segmented volumes were different, each had a relatively consistent result throughout the entire study.

Segmentation protocols used in Amira were performed on consecutive 2D slices, with each slice using the magic wand tool for area selection and subsequently a region-growing algorithm to relate serial slices. A specific optimal threshold value for each tooth was set visually to the level at which the tooth was clearly seen with minimal interference from surrounding bone. Visual adjustments of threshold parameters resulted in different threshold levels for different teeth in the same DICOM data sets, as well as between different data sets. Segmentation was mainly processed in the axial view from crown to the apex while the contrast parameters were changed for optimal observation.

In a previous study, it was reported that the mandibles show a better CBCT image quality than maxillae.[26] This could be due to a greater contrast between the dental alveolus and the cortex surrounding it, resulting in better visualization. Image quality of the maxillae creates a challenge in delineation of anatomic structures for segmentation. However, we did not find a difference between upper and lower teeth segmentation processes. We observed that the root density in both jaws was closer to cortical bone and readily visualized.[27] A problematic situation occurred when the teeth root were adjacent to cortical bone in the mandible, making segmentation relatively more difficult.

A smoothing function was used on the geometric model after segmentation. While this function enhances the visual appearance of the segmented tooth, it altered the final volume measurement. In this study, we lost 3% to 12% of the teeth volume with the use of the smoothing function. Therefore, one must take this into account when using tooth models created by segmentation for purposes, such as finite element analysis, and modeling of anchorage and other digital model applications.

CONCLUSIONS

- This is the first study to validate in vivo CBCT dental volumetric determinations.
- The measurements slightly deviate from the physical volumes within −4% to 7%. Smoothing operations reduce volume measurements by 3% to 12%.
- At this time, no requirements for accuracy of volumetric determinations of tooth volume have been established.

ACKNOWLEDGMENTS

The authors acknowledge Dr Ed Lin and Dr William Harrell, Foundation Saint Luc, Cliniques Universitaires Saint Luc, Université Catholique de Louvain.

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