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Accuracy of volumetric measurement of teeth *in vivo* based on cone beam computer tomography

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Structured Abstract

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Objectives – to evaluate the accuracy of cone beam computed tomography (CBCT) for volumetric measurement of teeth, using micro-computed tomography (Micro-CT) as the reference standard.

Setting and Sample Population – The Department of Orthodontics at Sichuan University. The sample consisted of 27 maxillary and mandibular premolars of 15 patients, planned to be extracted for orthodontic treatment.

Material and Methods – The 27 teeth were subjected to standardized CBCT scanning before extraction and Micro-CT scanning after extraction. From CBCT data, teeth were tissue segmented and then three-dimensionally (3D) reconstructed, while from Micro-CT data, teeth were 3D reconstructed directly. Tooth volumes were then calculated. The intra-observer repeatability and reproducibility of two observers and the overall between-instrument agreement of the measurements were evaluated using intra-class correlation coefficients (ICCs) and concordance correlation coefficient (CCC), respectively.

Results – The intra-observer repeatability was high for both observers. ICCs were 0.999 and 0.998, respectively. The reproducibility of the two observers was also high (ICC, 0.740). The overall between-instrument agreement of the measurements was good, and CCC was 0.993 and its lower 95% confidence interval was 0.989.

Conclusions – The accuracy of the CBCT method for volumetric measurement of teeth *in vivo* is comparable to the Micro-CT method *in vitro*. The CBCT method has the potential possibility to be applied in studies on root resorption associated with orthodontic force. Further study is needed to prove the sensitivity of the method.

Key words: cone beam computed tomography; quantitative methodology; root resorption

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Introduction

Root resorption associated with orthodontic force (RRAOF) is a common side effect of orthodontic treatment. For a long time, its clinical diagnosis had been mainly based on two-dimensional (2D) radiographic images, like panoramic (OPT) and periapical radiographs. These 2D images, however, are unable to detect root resorption on lingual and buccal surfaces. Furthermore, root resorption might be underestimated by OPT or periapical radiograph (1, 2). Reviewing current 2D X-ray-based tooth resorption appraisal protocols, Katona (3) concluded that none of the geometric measurement strategies of the currently existing 2D methods could reduce their errors enough to fulfill their pre-designed efficacy. That might partly explain the disparate or even conflicting results among studies on root resorption.

As root resorption is essentially a kind of volume loss, three-dimensional quantitative volumetric measurement should be much more precise in diagnosis of root resorption than qualitative or semiquantitative methods using 2D images (4, 5). The main 3D research techniques used now are scanning electronic microscopy (SEM) and micro-computed tomography (Micro-CT) (5, 6). As being utilized in studying the 3D structure of cancellous bone by Feldkamp et al. (7), Micro-CT has been widely applied in the medical field for its extraordinary high resolution, up to 3 μm, and could be considered as the reference standard in 3D dental studies (2, 8–10). Darendeliler colleagues (5, 11, 12) reported several Micro-CT or SEM volumetric analyses on root resorption. These studies introduced a new 3D method to detect root resorption and enhanced our insights into root resorption. Root resorption in these studies, however, was estimated by methods that could only be performed *in vitro*. Cone beam computed tomography (CBCT), which offers a 3D image of dental structures, has been widely used in the dental field (13–15). Compared with conventional computed tomography, the advantages of CBCT include a lower radiation dose, improved image accuracy, shorter scanning time, and less image artifacts (16–19). The diagnostic value of CBCT in detecting root resorption, however, has not been sufficiently studied.

Compared with Micro-CT, one significant advantage of CBCT in root resorption studies is that it could be used *in vivo*. *In vivo* scanning of teeth, however, shows images of both teeth and surrounding tissues, which might produce some errors in the following tissue segmentation, and finally could lead to imprecise measurement of teeth volumes. Furthermore, the accuracy of CBCT, with maximal 80 μm voxel size resolution, is only about one twentieth of that of Micro-CT. Therefore, before CBCT could be applied to diagnose root resorption *in vivo*, the accuracy of volumetric measurement of teeth, firstly, and then the sensitivity of detecting volume changes in root resorption based on CBCT must be carefully evaluated.

Therefore, in this study, the accuracy of volumetric measurement of teeth *in vivo* based on CBCT was evaluated and compared with that of Micro-CT *in vitro*, which served as the 'reference standard.'

Materials and methods

Twenty-seven maxillary and mandibular premolars without root canal therapy or periodontal diseases of 15 patients (eight boys, seven girls; mean age, 14.2 years; range, 12–22 years), which were planned to be extracted for orthodontic treatment, were included in this study. Before teeth extraction, patients were referred to CBCT scanning [MCT-1(EX-2F), J Morita Manufacturing, Kyoto, Japan; the scan parameters were as follows: voxel size resolution: 125 μm; tube voltage: 80 Kv; tube current: 5 mA].

Teeth were extracted utilizing a minimal invasive technique. Extracted teeth were sterilized in 10% of formaldehyde for about 10 h and rinsed in flowing water for 30 min and bench-dried for a minimum of 48 h (11, 20). Then, each tooth was fully examined under stereomicroscopy, especially around the apical area. A total of 30 teeth were collected, and 27 teeth were included. Three teeth were excluded because of surface damage.

The 27 extracted teeth were referred to Micro-CT scanning (μ80; Scanco Medical, Bassersdorf, Switzerland; scan parameters: voxel size resolution: 37 μm; tube voltage: 70 Kv; tube current: 114 μA).

Cone beam computed tomography scanning data were saved in DICOM (digital imaging and communications in medicine) format. Professional medical image software, Mimics (version 10.0; Materialise, Leuven, Belgium) was used for tissue segmentation, 3D reconstruction, and volumetric measurement.

Two observers repeated all the procedures twice independently. The observers were blinded to sample information like patient's name and tooth number. The within-observer repeatability and reproducibility of two observers were evaluated using intra-class correlation coefficients (ICCs) (18). ICC could be calculated as:

$$\frac{S_a^2 - S_d^2}{S_a^2 + S_d^2 + \frac{2}{n}\left(n\bar{d}^2 - S_d^2\right)}$$

S_a^2 is the estimated variance of the n sums;
S_d^2 is the estimated variance of the n differences;

$\bar{d}$ is the estimated mean of the differences (an estimate of the systematic difference); and

n is the sample size.

As well, Micro-CT data were saved in DICOM format. By another investigator, teeth were 3D reconstructed directly and volumetric measurements were then conducted.

Concordance correlation coefficient (21–23) was used to inspect the agreement of volumetric measurements of teeth by CBCT and Micro-CT methods. CCC could be calculated as:

$$\mathrm{CCC} = \frac{2S_{12}}{S_1^2 + S_2^2 + \left(\bar{Y}_1 - \bar{Y}_2\right)}$$

$$S_{12} = \frac{1}{n}\sum_{i=1}^{n}\left(Y_{i1} - \bar{Y}_1\right)\left(Y_{i2} - \bar{Y}_2\right)$$

$$S_j^2 = \frac{1}{n}\sum_{i=1}^{n}\left(Y_{ij} - \bar{Y}_j\right),\ j = 1, 2$$

$\bar{Y}_1$ and $\bar{Y}_2$ are the sample means of Y_1 and Y_2, respectively; n is the sample size.

Table 1. **Measurements of teeth volumes by cone beam computed tomography (CBCT) and micro-computed tomography (Micro-CT) methods. First and second CBCT measurement of each observer and mean of the four measurements. All volumes in mm^3**

	Teeth volumes (mm^3)					
	CBCT					Micro-CT
Tooth number	Observer 1		Observer 2		Mean	
1	559.87	554.65	550.23	550.10	553.71	552.21
2	669.38	671.21	678.21	675.92	673.68	675.29
3	565.63	560.21	555.26	559.23	560.08	553.73
4	534.29	530.29	538.65	533.59	534.21	509.19
5	507.27	508.23	524.83	520.84	515.29	515.64
6	474.38	474.12	470.15	471.43	472.52	473.01
7	525.16	523.21	520.64	523.73	523.19	520.83
8	551.59	555.30	561.70	558.43	556.75	560.30
9	707.54	702.56	694.37	697.49	700.49	686.83
10	570.87	573.65	571.14	572.41	572.02	576.44
11	534.04	538.75	539.56	538.69	537.76	544.75
12	552.15	549.08	552.18	550.54	550.99	552.97
13	459.56	450.43	450.32	450.93	452.81	447.90
14	447.20	448.92	449.86	445.71	447.92	452.58
15	419.48	412.54	411.50	409.51	413.26	395.40
16	390.78	387.34	384.94	385.43	387.12	379.39
17	631.11	629.59	625.54	623.82	627.52	612.40
18	574.25	574.38	578.63	577.93	576.30	576.21
19	554.32	543.23	545.34	550.12	548.25	548.32
20	525.39	534.27	521.37	532.01	528.26	530.52
21	487.75	477.12	473.18	479.39	479.36	480.39
22	534.01	539.01	545.28	536.94	541.06	539.10
23	489.12	479.34	477.91	488.25	483.66	488.97
24	516.50	521.84	519.76	526.50	521.15	522.34
25	556.98	553.56	563.01	567.39	560.24	560.76
26	576.06	570.71	580.02	584.01	577.70	585.02
27	549.87	541.47	540.19	544.30	543.96	543.78
Mean ± SD (mm^3)					534.70 ± 69.09	532.75 ± 69.50

The statistical analysis was processed with Microsoft Excel (Microsoft, Redmond, WA, USA) and SPSS (Release 13.0, standard version; SPSS, Chicago, IL, USA).

Participation in the study was voluntary, and the study was approved by the ethical board of Sichuan University. All diagnostic information obtained from the study was used in the further management of those patients who required it, at no extra cost to them.

Results

The 3D images reconstructed from the CBCT and Micro-CT data are shown in Figs1 and 2, respectively. Table 1 shows the volume of each tooth calculated from micro-CT and CBCT data.

The intra-observer repeatability was high for both observers. ICC was 0.999 and 0.998, respectively. The reproducibility of the two observers was also high (ICC, 0.740).

Figure 3 shows the data in 27 samples when the results from the CBCT method were plotted against those from the Micro-CT method. The estimated regression line was drawn through the midst of the points, which had a slope of 0.9994. CCC was 0.9932, and its lower 95% confidence interval was 0.9887. The agreement between CBCT method and Micro-CT method was good.

Fig. 1. 3D image reconstructed from cone beam computed tomography (CBCT) data.

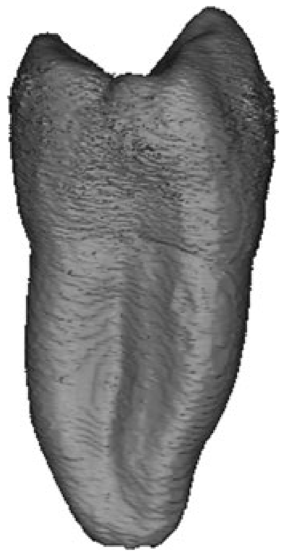

Fig. 2. 3D image reconstructed from micro-computed tomography (Micro-CT) data.

Discussion

Cone beam computed tomography is a new radiographic method with applications in orthodontics, implantology, oral surgery, endodontics, and temporomandibular joint imaging (24–27). Only a few studies have been performed into about the diagnostic value of CBCT to detect root resorption. Dudic et al. (1) explored the diagnostic ability of CBCT in detecting

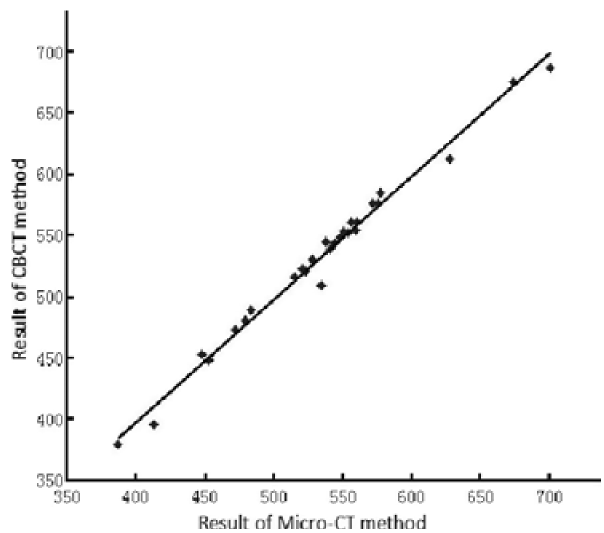

Fig. 3. A scatterplot of the results from two methods in 27 samples, which showed the agreement between the cone beam computed tomography (CBCT) method and the micro-computed tomography (Micro-CT) method. The solid line, whose slope was 0.9934, was the 'best-fit' for the observed data. If there were perfect agreement between these two methods, then the slope of the line should be close to 1.

root resorption compared with OPT, and they concluded that apical root resorption after orthodontic tooth movement was underestimated when evaluated on OPT. However, they still used 2D images in selective CT sections to detect root resorption, which were still semiquantitative methods, and the advantages of three-dimensional data were not fully utilized. Root resorption which occurs three-dimensionally is a kind of tooth volume loss. Three-dimensional quantitative measurement of volume changes pre- and post-orthodontic treatment, therefore, should be more precise for longitudinal and quantitative study of root resorption.

Because the densities of teeth and surrounding tissues varied among different individuals, a uniform threshold could result in data loss of teeth tissues in some samples. An individual segmentation threshold for each tooth, therefore, was employed in the CBCT-based method, to segment the hard tissue of teeth from surrounding tissues. It ranged from 1673 to 2000 Hounsfield (HU) in this study.

Criteria for selecting the threshold were as follows: ensuring intact teeth contour and eliminating surrounding tissues as possible. Fig. 4A showed fused teeth and surrounding tissues on the image, when the threshold was set too low (1406 HU). While Fig. 4B showed incomplete tooth contour on the image when the threshold was set too high (2189 HU). In Fig. 4C, with a suitable threshold (1688 HU), most of the surrounding tissues were eliminated and an intact tooth contour was ensured. Theoretically, teeth root could be separated by eliminating surrounding tissues after an appropriate threshold is set. *In vivo* CBCT scanning, however, may produce some artifacts in the periodontal ligament space between teeth and alveolar bones, which resulted in insufficient segmentation between teeth and surrounding tissues, as indicated by the arrow in Fig. 4C. For this situation, manual segmentations were required. In mimics, the investigator can use the 'edit masks' instrument to erase the artifacts to segment the teeth completely, as shown in Fig. 4D. It required cautions here to avoid erasing

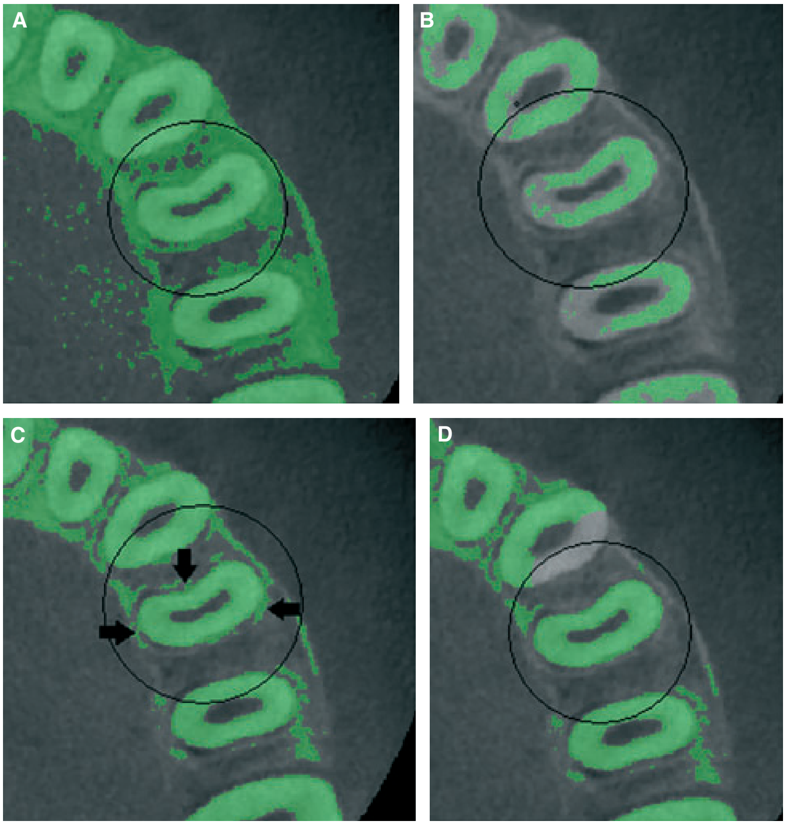

Fig. 4. (A) The threshold was set too low (1406 HU), which resulted in 'fusion' of teeth and surrounding tissues on the image. (B) The threshold was set too high (2189 HU), which resulted in incomplete tooth contour on the image. (C) With a suitable threshold (1688 HU), most of the surrounding tissues were eliminated and intact tooth contour was ensured. Insufficient segmentation between teeth and surrounding tissues, however, still existed (indicated by the arrow). (D) After manual segmentation, teeth were completely separated from the surrounding tissues. HU, Hounsfield.

normal teeth images. Only after teeth were segmented from bones completely, 3D reconstruction and then volumetric measurements could be successfully conducted. Root canal had a radiation density much lower than hard tissues and could be easily removed from the teeth by choosing a suitable threshold. In calculating the total volume of the tooth, only the hard tissue was included, while the canal was excluded.

With successful tissue segmentation, the 3D teeth model reconstruction could be easily performed as showed in Fig. 1. These impressive pictures could help orthodontists to examine the roots of the teeth directly and three-dimensionally. The precise volumetric measurement could be finished then by just one click of the mouse. This volumetric measurement based on CBCT introduced in this study could be conducted skillfully and reliably by investigators who had been trained for a short time. The high ICCs for intra-observer repeatability and reproducibility of two observers suggested satisfactory stability and reliable reproducibility of this CBCT method.

We found a good agreement between the CBCT method and Micro-CT method. The slope of the line was close to 1, and CCC was close to the maximum value of 1, indicating that there was good repeatability between the two sets of results and the accuracy of volumetric measurement of teeth based on CBCT was excellent.

Although volumetric measurement of teeth based on CBCT showed excellent accuracy in this study, it does not logically guaranty that this method also has enough sensitivity to detect the teeth volume changes occurring in root resorption. The questions remain whether this method could be utilized as a new precise quantitative method in studies about RRAOF. Further study is needed to explore the sensitivity of this CBCT method to detect different grades of root resorption.

Conclusions

In this study, we introduced an *in vivo* method of volumetric measurement of teeth based on CBCT. This CBCT method showed the same accuracy of volumetric measurement of teeth *in vivo* as Micro-CT did *in vitro*. The stability and reproducibility of this CBCT method were reliable and satisfactory. This volumetric measurement of teeth based on CBCT showed the potential possibility to be applied in studies about RRAOF, although further studies are needed.

Clinical relevance

Root resorption associated with orthodontic force which occurs at root surfaces irregularly and three-dimensionally (3D) is a kind of volume loss. To detect root resorption, precise 3D quantitative measurement of volume changes could have superior power to 2D measurement of changes of root length. The prerequisite of quantitative measurement of teeth volume changes, however, is accurate volumetric measurement of teeth. Therefore, the accuracy of CBCT for volumetric measurement of teeth *in vivo* was compared with that of Micro-CT *in vitro*.

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