Original Article

Precision, reproducibility, and accuracy of bone crest level measurements of CBCT cross sections using different resolutions

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ABSTRACT

Objective: To evaluate the precision, reproducibility, and accuracy of alveolar crest level measurements on CBCT images obtained with different voxel sizes.

Materials and Methods: CBCT exams were made of 12 dried human mandibles with voxel dimensions of 0.2, 0.3, and 0.4 mm. Bone crest level was measured directly on the mandibles with a digital caliper and on CBCT images. Images were measured twice by two examiners. Intra- and interexaminer precision and reproducibility were assessed using paired and *t*-tests, respectively. Accuracy was evaluated using *t*-tests.

Results: Precision and reproducibility of bone crest level tomographic measurements was good for all voxel sizes evaluated. The images with 0.2-mm voxel size showed a decreased number of intraexaminer errors. A high accuracy for measurements of bone crest level was observed for all CBCT definitions, except for the mandibular incisors using the 0.4-mm voxel size.

Conclusions: Precision and reproducibility of alveolar bone level measurements were good for various voxel sizes. CBCT images demonstrated good accuracy for 0.2-mm and 0.3-mm voxel sizes. The mandibular incisor region needs better resolution than that provided by 0.4-mm voxel size for bone crest level measurements. (*Angle Orthod.* 2016;86:535–542.)

KEY WORDS: Cone beam computed tomography; Alveolar bone; Reproducibility

INTRODUCTION

During the past decade, there has been an increasing use of three-dimensional (3-D) images to evaluate the craniofacial region. In this context, cone beam computed tomography (CBCT) has emerged, and it is especially indicated for evaluating maxillofacial morphology. Many investigators have measured buccal and lingual bone plate thickness with computed tomography.[1–4] The purpose of these studies was to evaluate bone thickness for mini-implant placement,[1] the morphology of bone tissue after orthodontic treatment,[3] and the reproducibility of alveolar bone measurements.[2]

A number of studies have demonstrated the precision of linear measurements performed on CBCT images.[5–8] Measurement precision is related to image resolution.[9] Spatial resolution of CBCT depends on the voxel dimension, which is the lowest image unit. A smaller voxel dimension leads to greater image resolution, but also to a higher dose of radiation.[10,11] Recent studies have shown higher accuracy and precision for CBCT with smaller voxel sizes.[2,4,12,13] However, no study has assessed the influence of voxel dimension on measurement accuracy and precision of natural bone crest level CBCT slices. Thus, the aim of the present study was to assess and compare the accuracy and reproducibility of alveolar crest level measurements with CBCT scans obtained with different voxel sizes. The null hypothesis is that the precision and accuracy of bone plate measurements is similar for CBCT cross sections with voxel sizes of 0.2, 0.3, and 0.4 mm.

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MATERIALS AND METHODS

Twelve dried human mandibles with permanent dentition were selected from the Anatomy Department at Bauru Dental School, University of São Paulo. CBCT scans were performed on each specimen with the i-Cat Cone Beam 3-D Dental Imaging System (Imaging Sciences International, Hatfield, Pennsylvania, USA). Each mandible was embedded in a cube of dental wax No. 7 with water and detergent to simulate soft tissue density. The base of the mandible was directly supported on the base of the box, parallel to the ground. The following image acquisition protocols were used for each specimen:

Protocol 1: Field of view (FOV) of 8 cm, 120 kVp, 36.12 mA, 0.2-mm voxel, 40-second scan time.

Protocol 2: FOV of 8 cm, 120 kVp, 18.45 mA, 0.3-mm voxel, 20-second scan time.

Protocol 3: FOV of 8 cm, 120 kVp, 18.45 mA, 0.4-mm voxel, 20-second scan time.

Thirty-six CBCT scans were performed, composing the overall sample.

Measurements of Bone Plate Level (Bone Dehiscence)

Physical measurements of bone crest level were conducted on the anatomical specimens using a digital caliper by examiner 1. For this purpose, lines representing the long axis of each tooth were drawn on each tooth root on the buccal and lingual aspects.

Using iCat Vision software (Imaging Sciences International), cross sections passing through the center of the long axis of each tooth were obtained (Figure 1). Lingual and labial or buccal bone crest level of all permanent teeth were measured from the cementoenamel junction (CEJ) to the limit of the lingual and labial or buccal alveolar bone crest, in each of the three image acquisition protocols, by examiners 2 and 3 (Figure 2).

Error Study

All physical measurements of bone crest level (examiner 1) and all tomographic bone crest level measurements (examiner 2) were performed twice, with a 1-month interval, representing the intraexaminer evaluations. Random errors were evaluated according to Dahlberg's formula[14] ($S^2 = \sum 2d/2n$), where S^2 is the error variance, and d is the difference between two determinations of the same variable. Systematic errors were evaluated with dependent *t*-tests at $P < .05$.

Statistical Analyses

Statistical analyses involved calculation of means and standard deviations of each physical and tomographic measurement, considering each group of teeth (incisors, canines, premolars, and molars). Precision and reproducibility of measurements were evaluated by the intraexaminer evaluation of examiner 2 and by comparison of measurements of examiners 2 and 3,

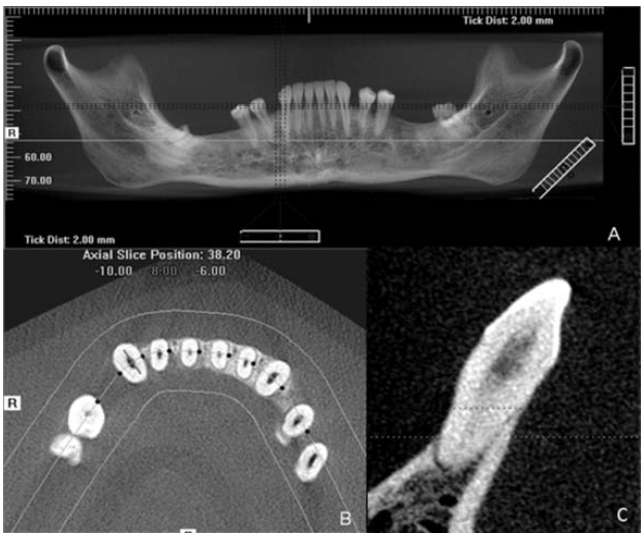

Figure 1. After uprighting the tooth's long axis in the panoramic reconstruction (A), an axial image passing at the level of the cervical region was obtained (B). Finally, a tooth cross-sectional image passing through the center of the crown was obtained (C).

Figure 2. Cross-sectional CBCT image showing measurement from the labial and lingual crest level to the CEJ.

Table 1. Intraexaminer Comparisons of the Physical Measurements of Bone Crest Level (Dahlberg's Formula and Paired *T*-Tests)

			1st Measurement (mm)		2nd Measurement (mm)				
		N	Mean	SD	Mean	SD	Difference	Dahlberg	*P*
I[a]	L	17	4.24	2.27	4.18	2.22	−0.06	0.26	.50
	Li	17	3.21	0.99	3.43	0.86	0.22	0.45	.15
C	L	13	4.17	2.21	4.18	2.28	0.01	0.16	.96
	Li	13	2.85	1.36	2.75	1.29	−0.10	0.36	.49
PM	B	25	4.45	2.39	4.32	2.33	−0.13	0.65	.49
	Li	25	3.37	1.35	3.46	1.38	0.09	0.52	.52
M	B	17	3.71	2.27	3.86	2.19	0.15	0.37	.28
	Li	17	3.97	2.26	3.98	2.16	0.01	0.41	.97

[a] I indicates incisors; C, canines; PM, premolars; M, molars; L, labial bone plate, B, buccal bone plate; and Li, lingual bone plate.

with the *t*-tests, respectively. Accuracy of bone crest level measurement was evaluated comparing the second physical measurement (examiner 1) and the tomographic measurements (examiner 3), using *t*-tests. Results were considered significant at $P < .05$.

RESULTS

Error Study and Precision of Tomographic Bone Plate Level Measurements

Results of the error study are shown in Tables 1 and 2. The random errors with the physical measurements were within acceptable ranges and there were no significant systematic errors (Table 1).

Evaluation of the tomographic intraexaminer measurements also consisted of evaluating the precision of tomographic bone plate measurements, which are displayed in Table 2. Random errors with the tomographic measurements were within acceptable ranges, and there was significant difference in measuring the molar lingual bone plate with a voxel size of 0.3 mm and the canine labial bone plate having a voxel size of 0.4 mm.

Reproducibility of Tomographic Bone Plate Level Measurements

There was no interexaminer significant difference in tomographic measurements (Table 3).

Accuracy of Tomographic Bone Plate Level Measurements

There was only one significant difference between the tomographic (voxel size, 0.4 mm) and physical measurements for the lingual bone plate of the incisors (Table 4).

DISCUSSION

The technology of CBCT is still new and few studies have evaluated the precision, reproducibility, and accuracy of tomographic measurements related to the image acquisition protocol.[2,4,12,13] One of the limitations of our study was the absence of soft tissue in the dry mandibles. Recently, Patcas et al.[13] found that the presence of soft tissue seems to have a curtailing effect on the accuracy of CBCT data when determining bony landmarks. In order to minimize this limitation, CBCT images were performed with specimens in water and detergent to simulate soft tissue density in the acquired images—a necessity in studies involving dry skulls, especially in those that aim to evaluate the reproducibility and accuracy of small linear distances.[9,15] However, there is no gold standard that accurately simulates the density of soft tissue. Cross sections were selected for bone crest level measurements instead of 3-D images because according to some authors, errors may occur in 3-D reconstructions because of the difficulty in locating points of linear measurement in 3-D spaces; there are inherent limitations of each program in the format of 3-D models.[16] It is necessary that quantitative evaluations be conducted within the multiplanar sections.[17] A recent study showed that multiplanar reformatted images are more suitable for linear measurements of calcified structures than are 3-D CBCT images.[18]

Precision, Reproducibility, and Accuracy of Tomographic Bone Plate Level Measurements

Recent studies have used higher resolution CBCT images from Accuitomo (J. Morita, Irvine, Calif) to evaluate alveolar bone and have concluded that this method of diagnosis is indicated when selecting the appropriate protocol.[19,20] Our study used the i-Cat Cone Beam 3-D Dental Imaging System (Imaging Sciences International), available at the institution where the project was developed. These results apply only to the i-Cat Cone Beam 3-D Dental Imaging System scanner; a different scanner with similar settings might give different results.

Tables 2 and 3 show that the tomographic bone crest level measurements were highly precise and reproducible, with differences in only one region for

Table 2. Intraexaminer Comparisons (Precision Evaluation) of Bone Crest Level Tomographic Measurements with Voxel Dimensions of 0.2-, 0.3-, and 0.4-mm (Dahlberg's Formula and Paired *T*-Tests)

			1st Measurement (mm)		2nd Measurement (mm)				
		N	Mean	SD	Mean	SD	Difference	Dahlberg	*P**
0.2-mm Voxel									
I[a]	L	17	3.42	1.64	3.51	1.82	0.09	0.33	.44
	Li	17	2.95	1.24	3.15	1.07	0.20	0.50	.26
C	L	13	3.64	1.56	3.84	1.68	0.20	0.68	.48
	Li	13	2.25	0.89	2.37	0.98	0.15	0.31	.33
PM	B	25	3.35	2.19	4.58	2.09	1.23	0.50	.11
	Li	25	3.45	1.50	3.63	1.41	0.18	0.54	.24
M	B	17	3.57	2.23	3.40	2.08	−0.17	1.93	.11
	Li	17	3.64	1.85	3.79	1.84	0.15	0.27	.23
0.3-mm Voxel									
I	L	17	2.84	1.19	3.31	1.89	0.47	1.23	.26
	Li	17	2.97	1.44	3.00	1.24	0.03	0.61	.92
C	L	13	3.09	1.14	3.45	1.27	0.36	0.64	.16
	Li	13	2.00	0.91	2.37	1.02	0.37	0.64	.14
PM	B	25	3.60	1.65	3.64	1.57	0.04	0.54	.82
	Li	25	3.79	1.54	3.47	1.52	−0.32	0.90	.15
M	B	17	3.82	2.15	3.42	2.29	−0.40	0.77	.13
	Li	17	4.07	1.99	3.36	1.94	−0.71	0.62	.00*
0.4-mm Voxel									
I	L	17	3.61	1.90	3.54	2.18	−0.07	0.70	.35
	Li	17	3.09	1.09	3.15	1.00	0.06	0.60	.80
C	L	13	3.73	1.33	3.29	1.19	−0.44	0.50	.02*
	Li	13	2.80	1.08	2.70	0.93	−0.10	0.24	.51
PM	B	25	4.09	1.51	3.80	1.54	−0.29	0.72	.17
	Li	25	3.50	1.49	3.50	1.41	0.00	0.47	.99
M	B	17	3.36	1.65	3.46	2.03	0.10	0.48	.55
	Li	17	3.66	1.54	3.46	1.67	−0.20	0.39	.14

[a] I indicates incisors; C, canines; PM, premolars; M, molars; L, labial bone plate; B, buccal bone plate; and Li, lingual bone plate.
*$P < .05$.

voxel sizes of 0.3 and 0.4 mm (Table 2). These results are in accordance with previous studies that evaluated small linear measurements as well.[2,6,15,21] Sun et al.[4] assessed the reproducibility of CBCT with different image acquisition protocols (0.25- and 0.4-mm voxel). They found that the agreement coefficient for bone height measurements was not affected by the CBCT resolution. These authors concluded that, overall, good to excellent repeatability can be achieved for alveolar linear measurements from CBCT images. The possible explanation is that, despite the distinct difference of sharpness between different resolution images, the rater can establish a method for linear measurements and maintain relative consistency using that method without its being affected by the sharpness of the CBCT image. Additionally, the authors concluded that linear measurement differences between the two resolution levels are inherent in the images rather than in the raters.[4]

The results of our study also demonstrated the high accuracy of tomographic measurements of alveolar bone crest level of the mandibular anterior and posterior teeth using 0.2- and 0.3-mm voxel sizes (Table 4). The 0.4-mm voxel size was not sufficiently accurate for the lingual aspects of the anterior teeth (Table 4). Many studies have identified high measurement accuracy of the bone crest level.[5,7,8,13,21] The highest accuracy of CBCT was identified by Mish et al.[7] using the i-Cat. In our study, the alveolar crest level was measured in CBCT cross sections. Mol and Balassundaram[15] also found poor accuracy of measuring bone dehiscence in the anterior mandible using the New Tom QR-DVT-9000 scanner (QR SRL, Verona, Italy). Lund et al.[21] and Patcas et al.[13] used the KAVO 3D exam scanner and found it to be accurate for bone crest level measurement of the mandibular anterior teeth with voxel sizes of 0.4 and 0.125 mm. The latter size was more precise than the former. However, the authors concluded that bone dehiscence may be overestimated in regions having thin bone plates (1 mm), regardless of voxel size.[13] In order to investigate the accuracy and reliability of buccal alveolar bone height and thickness measurements derived from CBCT images, Timock et al.[8] measured buccal alveolar bone height and thickness of 65 teeth of 12 embalmed cadaver heads in CBCT images using the i-CAT 17-19 unit (Imaging Sciences International) at 0.3-mm voxel size. The measurements were performed by two examiners three times. According to the results, CBCT can be used to

Table 3. Interexaminer Comparisons (Reproducibility Evaluation) of Bone Crest Level Tomographic Measurements With Voxel Dimensions of 0.2-, 0.3-, and 0.4-mm (*T*-Tests)

			Second Examiner (mm)		Third Examiner (mm)			
		N	Mean	SD	Mean	SD	Difference	*P**
0.2-mm Voxel								
I[a]	L	17	3.42	1.64	3.73	1.61	0.31	.58
	Li	17	2.95	1.24	2.95	1.41	0.00	.99
C	L	13	3.64	1.56	3.66	1.28	0.02	.98
	Li	13	2.25	0.89	2.49	0.94	0.24	.52
PM	B	25	3.35	2.19	4.31	1.50	0.96	.94
	Li	25	3.45	1.50	3.25	1.50	−0.20	.64
M	B	17	3.57	2.23	4.15	2.34	0.58	.46
	Li	17	3.64	1.85	3.76	1.77	0.12	.85
0.3-mm Voxel								
I	L	17	2.84	1.19	3.04	1.66	0.20	.67
	Li	17	2.97	1.44	2.73	1.50	0.24	.63
C	L	13	3.09	1.14	3.27	1.48	0.18	.72
	Li	13	2.00	0.91	2.17	0.73	0.10	.61
PM	B	25	3.60	1.65	3.49	1.53	−0.11	.81
	Li	25	3.79	1.54	3.42	1.28	−0.37	.36
M	B	17	3.82	2.15	3.76	2.16	−0.06	.94
	Li	17	4.07	1.99	3.90	1.96	−0.17	.81
0.4-mm Voxel								
I	L	17	3.61	1.90	3.72	1.79	0.11	.86
	Li	17	3.09	1.09	2.68	0.96	−0.41	.25
C	L	13	3.73	1.33	3.69	1.12	−0.04	.93
	Li	13	2.80	1.08	2.55	1.13	−0.25	.62
PM	B	25	4.09	1.51	3.67	1.35	−0.42	.30
	Li	25	3.50	1.49	3.44	1.53	−0.06	.89
M	B	17	3.36	1.65	3.42	1.76	0.06	.92
	Li	17	3.66	1.54	3.74	1.61	0.08	.87

[a] I indicates incisors; C, canines; PM, premolars; M, molars; L, labial bone plate; B, buccal bone plate; and Li, lingual bone plate. * $P < .05$.

quantitatively assess buccal bone height and buccal bone thickness with high precision and accuracy. When the authors compared the two sets of CBCT measurements, buccal bone height was found to have greater reliability and agreement with direct measurements than did the buccal bone thickness measurements.[8] In an animal study, Sherrard et al.[22] employed the same image acquisition protocols used in the present study (0.2-, 0.3-, and 0.4-mm voxels) for measuring the length of teeth and roots. A small difference between the different protocols (<0.3 mm) was found. In the same year, Damstra and colleagues[12] evaluated measurements of 3-D images of dried mandibles obtained with the 3D eXam scanner (KaVo Dental GmbH, Bismarckring, Germany) and voxels of 0.25 and 0.40 mm. The authors measured the mandibular dimensions established by preattached markers and found no difference between the two protocols.

Regarding the voxel sizes, there was one error with the 0.4-mm voxel protocol and these results corroborate those reported by Sun et al.[4] (Table 4). Decreasing the CBCT voxel size from 0.4 to 0.25 mm can improve the accuracy of tomographic alveolar bone linear measurements. Interestingly, Sun et al.[4] found that bone plate thickness influences the precision of the alveolar crest level measurement. In regions with thick bone plates, bone crest level are overestimated while in regions with thin bone plates, bone crest levels are underestimated.

A recent study compared protocols having different voxel sizes (0.4 mm and 0.2 mm) to evaluate alveolar bone height measurements.[23] CBCT exams were performed using the i-Cat Platinum scanner (Imaging Sciences International). The results demonstrated that the 0.2-mm voxel size protocol was more precise for alveolar bone height measurements.[23] CBCT imaging can provide accurate and reliable measurements of buccal alveolar bone using either of two diverse acquisition settings, unless higher resolution imaging for other purposes is necessary.[24]

Partial volume average property occurs when a specific voxel involves two structures of different densities, such as periodontal ligament and alveolar bone, for example. The density assigned to this voxel will be equivalent to the average density of the two tissues.[25] This property of computed tomography impairs clear visualization of the limit of delicate anatomical structures such as alveolar bone plates. Alveolar bone thickness smaller than the spatial

Table 4. Comparisons Between Tomographic Measurements (With Different Voxel Sizes) and Physical Measurements of Bone Crest Level (Accuracy Evaluation, *T*-Tests)

			Physical Measurement (mm)		CBCT Measurement (mm)			
		N	Mean	SD	Mean	SD	Difference	*P**
0.2-mm Voxel								
I[a]	L	17	4.18	2.22	3.73	1.61	−0.45	.50
	Li	17	3.43	0.86	2.95	1.41	−0.48	.23
C	L	13	4.18	2.28	3.66	1.28	−0.52	.48
	Li	13	2.75	1.29	2.49	0.94	−0.26	.55
PM	B	25	4.32	2.33	4.31	1.50	−0.01	1.00
	Li	25	3.46	1.38	3.25	1.50	−0.21	.60
M	B	17	3.86	2.19	4.15	2.34	0.29	.70
	Li	17	3.98	2.16	3.76	1.77	−0.22	.75
0.3-mm Voxel								
I	L	17	4.18	2.22	3.04	1.66	−1.14	.10
	Li	17	3.43	0.86	2.73	1.50	−0.70	.10
C	L	13	4.18	2.28	3.27	1.48	−0.91	.24
	Li	13	2.75	1.29	2.17	0.73	−0.58	.17
PM	B	25	4.32	2.33	3.49	1.53	−0.83	.14
	Li	25	3.46	1.38	3.42	1.28	−0.04	.91
M	B	17	3.86	2.19	3.76	2.16	−0.10	.90
	Li	17	3.98	2.16	3.90	1.96	−0.08	.91
0.4-mm Voxel								
I	L	17	4.18	2.22	3.72	1.79	−0.46	.51
	Li	17	3.43	0.86	2.68	0.96	−0.75	.02*
C	L	13	4.18	2.28	3.69	1.12	−0.49	.49
	Li	13	2.75	1.29	2.55	1.13	−0.20	.67
PM	B	25	4.32	2.33	3.67	1.35	−0.65	.24
	Li	25	3.46	1.38	3.44	1.53	−0.02	.96
M	B	17	3.86	2.19	3.42	1.76	−0.44	.53
	Li	17	3.98	2.16	3.74	1.61	−0.24	.73

[a] I indicates incisors; C, canines; PM, premolars; M, molars; L, labial bone plate; B, buccal bone plate; and Li, lingual bone plate. * $P < .05$.

resolution of the image may not be apparent in the tomographic image, resulting in a false-positive diagnosis of bone dehiscence, which explains Patcas's[13] results. For quantitative assessments, partial volume average may underestimate bone ridge levels.[4]

Image quality can be influenced by several factors such as bit depth,[11] detector type, exposure time,[11,26] and voxel gray tone.[26] The last can be influenced by the field of view and artifacts caused by beam hardening and X-ray attenuation by dense materials.[26] The field of view and detector type were the same for the various protocols used in this study. On the other hand, exposure time was 40 and 20 seconds for voxel sizes of 0.2 and 0.4 mm, respectively. However, exposure time is automatically set for the scanner when voxel size is selected. Image quality can also be affected by milliamperage (mA). The lower the mA, the lower is the dose of radiation and image quality.[27] This study evaluated protocols with different mAs, in which protocol 1 had 36.12 mA while protocols 2 and 3 had 18.45. However, according to Vasconcelos et al.,[28] image quality is not significantly improved when the mA increases above 6.3, while a level below 6.3 mA results in image quality degradation.[28] Therefore, the differences in mA used in our study might not have influenced the image quality of every protocol.

Considering that CBCT allows a more accurate appreciation of the alveolar bone, a statistical difference equal to or greater than 0.5 mm would have clinical significance for alveolar bone level measurements. In this perspective, only the error at the lingual aspect of molars with a 0.3-mm voxel size was considered clinically significant (Table 2).

Considering the growing applicability of CBCT in dentistry, it is important to determine which image acquisition protocol is capable of providing a 3-D image with the appropriate resolution and sharpness for measuring small structures such as buccal and lingual bone plates.[2,4,7,8,13] A smaller voxel dimension offers greater spatial resolution, but a larger dose of radiation is delivered.[10] Thus, voxel dimension is directly related to the radiation dose and for this reason it is necessary to establish the cost-benefit ratio based on the ALARA (as low as reasonably achievable) principle before selecting the image acquisition protocol.[29] In other words, the protocol should be chosen based on the lowest possible radiation dose while offering sufficient sharpness for identification of the structures to be evaluated. The results of the present study demonstrated good precision, reproducibility, and accuracy for measuring the bone crest level of mandibular posterior teeth on tomographic images

and mandibular anterior teeth for 0.2 and 0.3 voxel sizes. On the other hand, for secure identification of bone crest level, the mandibular anterior teeth covered by a thin bone plate would need a better image resolution with a voxel size smaller than 0.4 mm.

CONCLUSIONS

- Measurements of alveolar bone crest levels of the mandibular posterior teeth on CBCT images demonstrated good accuracy.
- The mandibular incisor region needs better resolution than that provided by 0.4 mm of voxel size for bone crest level measurements.
- Precision of alveolar bone level measurements was similar for different voxel sizes.

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