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Accuracy and reliability of buccal bone height and thickness measurements from cone-beam computed tomography imaging

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Introduction: Cone-beam computed tomography (CBCT) imaging has broadened opportunities for examining morphologic aspects of the craniofacial complex, including alveolar bone, but limitations of the technology have yet to be defined. Through the use of comparisons with direct measurements, the purpose of this study was to investigate the accuracy and reliability of buccal alveolar bone height and thickness measurements derived from CBCT images. **Methods:** Twelve embalmed cadaver heads (5 female, 7 male; mean age: 77 years) were scanned with an i-CAT 17-19 unit (Imaging Sciences International, Hatfield, Pa) at 0.3 mm voxel size. Buccal alveolar bone height and thickness measurements of 65 teeth were made in standardized radiographic slices and compared with direct measurements made by dissection. All measurements were repeated 3 times by 2 independent raters and examined for intrarater and interrater reliability. Measurement means were compared with 2-tailed *t* tests. Agreement between direct and CBCT measurements was assessed by concordance correlation coefficients, Pearson correlation coefficients, and Bland-Altman plots. **Results:** Intrarater reliability was high as were interrater correlations for all measurements ($\geq$0.97) except CBCT buccal bone thickness (0.90). CBCT measurements did not differ significantly from direct measurements, and there was no pattern of underestimation or overestimation. The mean absolute differences were 0.30 mm in buccal bone height and 0.13 mm in buccal bone thickness with 95% limits of agreement of −0.77 to 0.81 mm, and −0.32 to 0.38 mm, respectively. Agreement between the 2 methods was higher for the measurements of buccal bone height than buccal bone thickness, as demonstrated by concordance correlation coefficients of 0.98 and 0.86, respectively. **Conclusions:** For the protocol used in this study, CBCT can be used to quantitatively assess buccal bone height and buccal bone thickness with high precision and accuracy. Comparing the 2 sets of CBCT measurements, buccal bone height had greater reliability and agreement with direct measurements than did the buccal bone thickness measurements. (Am J Orthod Dentofacial Orthop 2011;140:734-44)

Orthodontists have historically relied on 2-dimensional imaging to aid diagnosis and treatment planning as well as to monitor treatment progress and growth. This traditional imaging approach limits analysis to linear and angular measurements between landmarks superimposed onto a single plane of space, often leading to distortion errors. Conventionally, the most accurate measures have relied on direct evaluation of patients or objects, and this remains the standard from which to judge other measurement techniques. With the advent of 3-dimensional imaging modalities such as conventional computed tomography (CT) and cone-beam CT (CBCT), practitioners can now visualize and measure the true 3-dimensional anatomy of patients. In addition to avoiding the intrinsic weaknesses of 2-dimensional imaging (distortion, superimposition), CBCT also allows measurements to be made in planes of space not available or accurately depicted in traditional radiographs.[1] However, limits to the accuracy of CBCT measurements have not been well defined.

For several decades, conventional CT has been used selectively for imaging of the craniofacial region—eg, to

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evaluate the temporomandibular joint,[2] osseous pathology,[3] deformities, and asymmetries.[4] However, drawbacks including cost, equipment size, and risks associated with relatively high radiation doses have made conventional CT impractical for many dental applications.

Increasingly over the past decade, CBCT imaging has been advocated for head and neck applications due in part to advantages of reduced cost and radiation exposure relative to conventional CT technology. Multiple orthodontic applications have been described including locating impacted teeth,[5,6] quantification of bone modeling, displacement in response to orthognathic surgery[7,8] or growth modification,[9] 3-dimensional analysis of facial asymmetries, soft tissues, and airways,[10] visualization of root resorption and inclination,[11,12] and improved cephalometric landmark identification.[13] By offering isotropic voxels (volumetric pixels that are identical length in all 3 dimensions) ranging from as small as 0.07 to 0.25 mm, CBCT potentially provides a means to accurately measure the craniofacial complex in detail.[1] For example, investigators have used CBCT to document changes in buccal bone dimensions after rapid palatal expansion[14] and archwire expansion of the dental arches.[15]

A potential side effect of buccal orthodontic tooth movement on the alveolus has previously been demonstrated in animal studies and histologic examinations.[16,17] In monkey[16] and dog[17] models, bony dehiscences of tooth roots have been produced by such tooth movements with little correlation to connective tissue attachment loss. Because such deterioration of underlying periodontal structures might not be reflected in the clinical appearance of the dentition and the soft tissues, orthodontists might be blinded to the creation of irreversible hard-tissue changes that could accompany such tooth movements. Because histologic cross-sections are not a realistic option in patients and routine soft-tissue reflection is impractical and potentially damaging, the unique combination of submillimeter resolution with multiple display modes (eg, oblique or nonorthogonal orientation) and real-time analysis and enhancement options (eg, reformatting images or realigning slices) potentially makes CBCT imaging ideal for evaluating alveolar bone changes associated with orthodontic treatment.

Whereas CBCT imaging is generally regarded as inherently accurate, to date there are limited published reports confirming this. Studies that have examined accuracy favor CBCT over more traditional imaging modalities such as cephalograms[13,18] and periapical radiographs,[19] as well as conventional CT.[20] However, compared with direct anthropometric measurements, the results of several CBCT investigations suggest that further inquiries are warranted to better define the limitations of measurements derived from CBCT imaging. As examples, Lascala et al[21] found that CBCT-derived measurements consistently underestimated direct measurements over large distances (30-100 mm), with differences ranging from 3.43 to 6.59 mm. Baumgaertel et al[22] showed a similar trend for underestimating dental measurements such as mesiodistal tooth widths and overjets on dry skulls, with these differences becoming significant for values such as available arch length when calculated from multiple measurements. Lastly, Berco et al[23] found that distances between traditional cephalometric landmarks made on images of dry skulls had statistically significant mean measurement errors compared with direct measurements.

The findings of statistically significant measurement errors in the studies above that were made under ideal laboratory conditions justify caution in accepting the premise that clinically related CBCT images are fundamentally accurate. Additionally, variations in imaging parameters, subjects, and structures of interest make it difficult to confidently apply the results more broadly to structures and clinical conditions that have not yet been investigated. With clinical studies relying on CBCT imaging currently reaching the literature in an attempt resolve an orthodontic controversy regarding the effects on alveolar bone when teeth are moved facially, it is essential to investigate the accuracy of the technique under conditions that replicate clinical imaging.[14,15]

The purpose of this study was to investigate the reliability and accuracy of measurements of alveolar buccal bone height and thickness from CBCT scans of cadaver heads relative to direct measurements acquired after dissection by using multiple measures of reliability and agreement.

MATERIAL AND METHODS

Human cadaver specimens were made available through the Department of Integrative Biosciences, School of Dentistry, Oregon Health and Science University, Portland, Ore, after review and approval of the study's protocol by the institutional review board. A preliminary screening of 17 subjects was performed, with 12 dentate cadavers fulfilling the initial selection criteria of no full-mouth restorations, no clinically observable oral pathology or mechanical damage in the oral region, and no prior dissection of the craniofacial complex. The sample consisted of 5 female and 7 male subjects, all white, with ages ranging from 55 to 89 years (mean, 77 years). A final sample of 65 teeth was selected by direct observation based on the following inclusion criteria: (1) no alloy restoration in the tooth itself or adjacent teeth, (2) intact crown, and (3) a periodontium without embalming-related artefacts such as pins or wires. To help distribute the sampling among all specimens,

Table I. Distribution of teeth examined by tooth type

Tooth type	*Maxilla*	*Mandible*	*Total*
Anterior			
Central incisor	14	21	35
Lateral incisor	0	2	2
Canine	2	9	11
Anterior total	16	32	48
Posterior			
First premolar	1	8	9
Second premolar	1	5	6
First molar	1	0	1
Second molar	1	0	1
Posterior total	4	13	17
Total	20	45	65

maximums of 4 anterior and 4 posterior teeth were selected from each cadaver. Table I shows the distribution of the teeth examined by tooth type. To facilitate the logistics of CBCT imaging, before transport, all specimens were disarticulated below the shoulder.

The CBCT scans were acquired using an i-CAT 17-19 CBCT unit (Imaging Sciences International, Hatfield, Pa) by using the technical parameters and settings listed in Table II. The cadaver specimens were wrapped in a plastic barrier and placed on top of a base in the i-CAT motorized chair. Each specimen was oriented to replicate normal patient positioning and secured with a chin support, a head support, and a forehead strap. A preview image was then exposed to validate the appropriate head positioning before acquiring the CBCT scan. The CBCT scans were saved as digital imaging and communications in medicine (DICOM) files.

After the CBCT scans, the specimens were dissected by using a full-thickness buccal flap reflected around each tooth of interest. Buccal bone height was measured by using a digital vernier caliper (General Tools, New York, NY) with a reading to the nearest 0.01 mm. Buccal bone height was defined as the linear distance from the incisal edge or the buccal cusp tip to the buccal alveolar crest along the long axis of the tooth (Fig 1, *A* and *B*). The coronal reference point was defined as the mesiodistal center of the incisofacial (or occlusofacial) line angle of the tooth of interest. The apical reference point was defined as the mesiodistal center of the root surface at the height of the buccal bone plate. For rotated teeth, the mesiodistal width was measured from contact to contact of adjacent teeth, and measurements were made in the plane of space perpendicular to the dental arch form (Fig 1, *C*). In cases of maxillary molar measurements, the mesiobuccal cusp and root were measured.

In preparation for the buccal bone thickness measurements, a section of buccal alveolar bone approximately 3 mm in height was removed from the most coronal aspect of the alveolar bone along the long axis

Table II. i-CAT 17-19 technical parameters and settings

Technical parameter	*Value*
Manufacturer	Imaging Sciences International, Hatfield, Pa
X-ray source voltage	120 kVp
X-ray source current	3-8 mA (pulse mode)
Focal spot size	0.5 mm
X-ray beam size	0.5 × 0.5–8 × 10 in
Scanning time	8.9 s
Total number of pulses	309
Image acquisition rotation	360°
Image detector	Amorphous silicon flat panel detector
Gray scale	12 bit
Field of view	Landscape 13 mm
Voxel size	0.3 mm

of the tooth (Fig 1, *D*). Buccal bone thickness was measured in the mesiodistal center of the newly exposed root surface from the most buccal cortical bone to the cementum by using a modified depth gauge accurate to 0.01 mm held parallel to the occlusal plane (Fig 1, *E*). To account for the effect of rotations on the measured bone thickness, the measurements were made in the plane of space perpendicular to the dental arch form.

For both buccal bone height and buccal bone thickness values, 2 investigators (A.T., V.C.) each made 3 independent measurements, with a minimum interval of 1 day between measurements. Additionally, to measure buccal bone thickness at the same bone level in the CBCT images, each investigator measured the height at which the buccal bone thickness values were measured relative to the coronal reference point (Fig 1, *F*), and the average was cross-referenced during the CBCT measurements.

The DICOM files were imported into Dolphin 3D Imaging (Dolphin Imaging Systems, Chatsworth, Calif) for analysis. As with the direct measurements, 3 separate CBCT measurements of buccal bone height and buccal bone thickness were made independently by the same 2 investigators, with a minimum interval of 1 day between recordings. The measurements were made in the appropriate sectional slice of 0.5 mm thickness in a darkened room. A standardized orientation was established, and a step-by-step protocol was followed.

1. The image was oriented so that the occlusal plane was parallel to the axial plane in the frontal and lateral views, and the head's midline was bisected by the midsagittal plane (Fig 2, *A*).
2. The axial plane was selected to intersect with the crown of the tooth of interest (Fig 2, *B*).
3. The coronal and sagittal planes were adjusted to pass through the center of the crown and root of

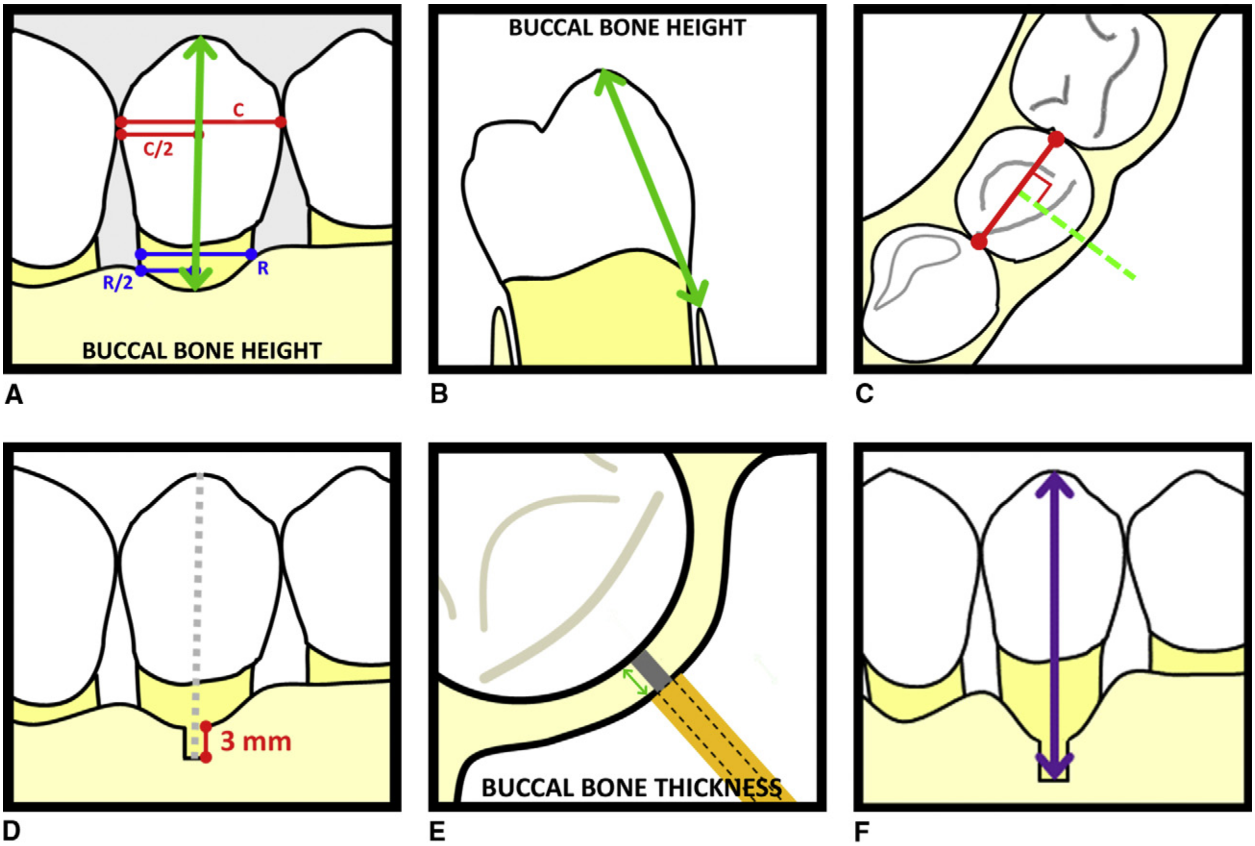


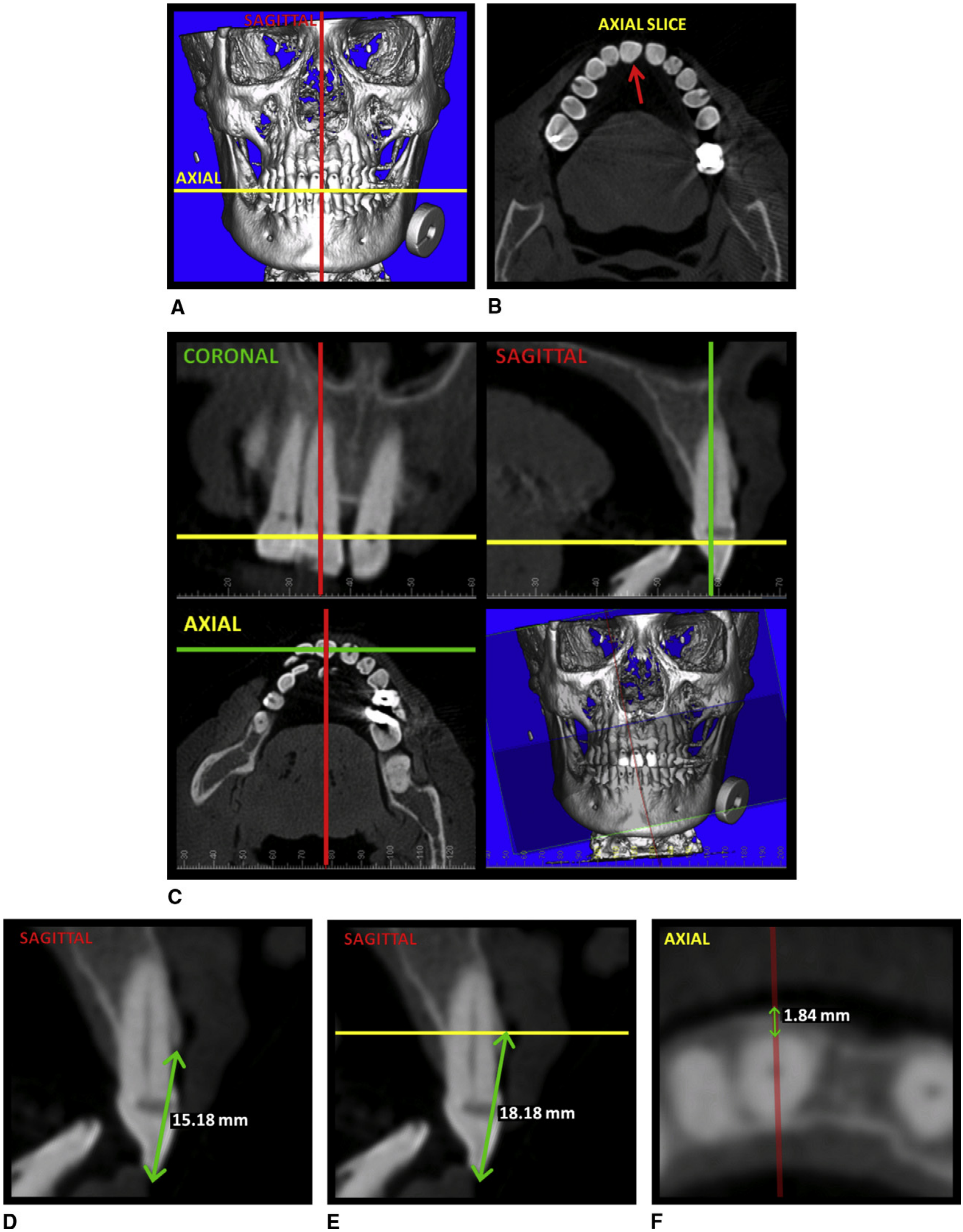
Fig 1. Illustrations of the direct measurement protocol: **A** and **B,** buccal bone height (*green arrow*) measured from the incisal edge or the buccal cusp tip to the alveolar crest following the long axis of the tooth; **C,** when a tooth was rotated, the mesiodistal locations for buccal bone height and buccal bone thickness measurements were determined by bisecting the width between contacts with adjacent teeth (*red line*) and projecting this point perpendicularly to the crest of the alveolar bone (*green dashed line*); **D,** approximately 3 mm of alveolar bone was removed before buccal bone thickness measurements at the same mesiodistal location along the alveolar crest as the buccal bone height apical landmark; **E,** buccal bone thickness (*green arrow*) was defined as the distance from the buccal aspect of the alveolar bone to the newly exposed root surface at the apical base of the dissection; **F,** each investigator measured the height (*purple arrow*) at which the buccal bone thickness values were measured relative to the coronal reference point, and the average was cross-referenced during the CBCT measurements of buccal bone thickness.

the tooth of interest (dilacerated apices were ignored), with the sagittal plane perpendicular to the subject's arch form in the axial view (Fig 2, *C*).

4. By using the sagittal view, buccal bone height was measured from the most incisal (or occlusal) and buccal aspects of the tooth to the most coronal aspect of the buccal alveolar bone crest (Fig 2, *D*).
5. The apical reference point identifying the alveolar crest was dragged apically along the buccal aspect of the alveolar bone to the height at which the direct buccal bone thickness measurements were made as described above (Fig 2, *E*).
6. The axial plane was adjusted to the height established in step 5 (Fig 2, *E*), and buccal bone thickness was measured from the most buccal aspect of the root to the most buccal aspect of the alveolar bone along the orientation of the sagittal plane (Fig 2, *F*).

Statistical analysis

A generalizability analysis was performed by using EduG (version 6.0; Swiss Society for Research in Education Working Group, Neuchatel, Switzerland) to assess


SAGITTAL
AXIAL
A
AXIAL SLICE
B
CORONAL
SAGITTAL
AXIAL
C
SAGITTAL
15.18 mm
D
SAGITTAL
18.18 mm
E
AXIAL
1.84 mm
F

the sources of error variation for both buccal bone height and buccal bone thickness measurements. Data from repeated measurements were pooled to examine interrater reliability within the method.

Interrater reliability was described by mean differences and mean absolute differences (positive or negative signs ignored), and further analyzed by calculating concordance correlation coefficients[24] and Pearson correlation coefficients by using Stata statistical software (release 11.0; StataCorp, College Station, Tex) for 4 sets of data: direct measurements of buccal bone height, direct measurements of buccal bone thickness, CBCT measurements of buccal bone height, and CBCT measurements of buccal bone thickness. The concordance correlation coefficient, although similar to the Pearson correlation coefficient in measuring the linear relationship, or association, between 2 sets of data, also takes into account any departure from a line of perfect agreement such as a scale or a location shift.[24]

Overall measurement accuracy was evaluated by using pooled data from both raters. Comparisons of means, mean differences, and mean absolute differences between the direct and CBCT methods were made in addition to concordance and Pearson correlation coefficients. Two-tailed paired t tests were performed to examine differences between means derived from the 2 measurement methods, with the level of significance set to $P \leq 0.05$. Agreement between direct and CBCT measurements was analyzed with Bland-Altman plots by using 95% limits of agreement (average differences ± 1.96 of the standard deviation of the differences).[25]

RESULTS

The generalizability analysis showed that the percentages of variance due exclusively to the timing of the measurements were small: 0.0% and 0.3% for buccal bone height and buccal bone thickness, respectively. Including all interactions of time with the other variables (rater, method, and subject), additional values of 1.4% and 11.3% of variance, respectively, were associated in part to time. Because the amount of variance from the repeated measures was minimal, and to facilitate the analysis of the reliability between raters, the data were pooled across time points.

Table III displays the descriptive statistics for the agreement between raters for buccal bone height and buccal bone thickness measured directly and from CBCT images. The concordance and the Pearson correlation coefficients between raters for the direct measurements of buccal bone height and buccal bone thickness were extremely high (≥ 0.98). The concordance and the Pearson correlation coefficients for CBCT buccal bone height measurements also demonstrated excellent agreement and reliability (0.98 for both), whereas buccal bone thickness measurements showed more modest agreement (0.90 and 0.91, respectively).

Table IV shows the descriptive statistics for overall measurement accuracy of the direct and CBCT methods. For buccal bone height, the means and standard deviations for both methods were comparable (12.32 ± 2.22 mm and 12.34 ± 2.21 mm, respectively), with the resulting mean difference close to zero (0.02 ± 0.40 mm). The Bland-Altman 95% limits of agreement for buccal bone height were -0.77 to 0.81 mm, with a range of ± 0.79 mm from the mean difference (Fig 3, *A*). The distribution showed that 54% of the CBCT buccal bone height measurements were greater than the corresponding direct measurement values, and 43% were smaller (3% were the same). There also did not appear to be any relationship between the magnitude or direction of the difference between CBCT and direct measures and the average of direct and CBCT buccal bone height measurements. Ignoring the sign of the difference between the 2 techniques, the mean absolute difference was 0.30 ± 0.27 mm. Agreement was excellent between the 2 methods, with both concordance and Pearson correlation coefficients of 0.98. The 2-tailed paired t test demonstrated no significant difference between the CBCT and the direct buccal bone height measurements.

For buccal bone thickness, the means and standard deviations of both direct and CBCT measurements were approximately equal (0.54 ± 0.35 mm and 0.52 ± 0.33 mm, respectively) with a mean difference of 0.03 ± 0.18 mm between them. The 95% limits of agreement for buccal bone thickness were -0.32 to 0.38 mm, with

Fig 2. CBCT measurement protocol: **A,** initial orientation of the image in the 3-dimensional volumetric view; **B,** the axial plane was adjusted to pass through the crown of the tooth of interest (*red arrow*); **C,** the coronal and sagittal planes were oriented to pass through the long axis of the tooth of interest with the sagittal plane oriented perpendicular to the arch form as viewed in the axial plane; **D,** measurement of buccal bone height (*green arrow*) was made in the sagittal plane from the incisal edge (or the buccal cusp tip) to the alveolar bone crest; **E,** to measure buccal bone thickness, the axial plane (*yellow line*) was repositioned to the height recorded for the direct buccal bone thickness measurement (Fig 1, *F*); **F,** buccal bone thickness was measured (*green arrow*) in the axial plane from the root surface to the buccal aspect of the alveolar bone along the orientation of the sagittal plane (*red line*).

Table III. Interrater agreement as demonstrated by mean difference (Mean Diff), mean absolute difference (Mean Abs), standard deviation (SD), concordance correlation coefficient (CCC), and Pearson correlation coefficient (PCC)

	Direct		*CBCT*	
	BBH	*BBT*	*BBH*	*BBT*
Mean Diff ± SD (mm)	0.01 ± 0.10	0.01 ± 0.06	0.11 ± 0.45	0.03 ± 0.06
Mean Abs ± SD (mm)	0.08 ± 0.06	0.05 ± 0.04	0.33 ± 0.32	0.12 ± 0.10
CCC	0.999	0.984	0.978	0.898
PCC	0.999	0.986	0.980	0.909

BBH, Buccal bone height; *BBT*, buccal bone thickness.

Table IV. Measurement accuracy of BBH and BBT by mean, mean difference (Mean Diff), mean absolute difference (Mean Abs), standard deviation (SD), and concordance correlation coefficient (CCC) with 95% confidence interval (CI)

	Direct	*CBCT*	*Difference (direct-CBCT)*	*Difference (direct-CBCT)*	
Variable	*Mean ± SD (mm)*	*Mean ± SD (mm)*	*Mean Diff ± SD (mm)**	*Mean Abs ± SD (mm)†*	*CCC (95% CI)*
BBH	12.32 ± 2.22	12.34 ± 2.21	0.02 ± 0.40	0.30 ± 0.27	0.984 (0.973, 0.992)
BBT	0.52 ± 0.33	0.54 ± 0.35	0.03 ± 0.18	0.13 ± 0.12	0.859 (0.779, 0.912)

BBH, Buccal bone height; *BBT*, buccal bone thickness.
*Mean difference between each direct and CBCT measurement; †Mean of the absolute difference between each direct and CBCT measurement.

a range of ±0.35 mm from the mean difference (Fig 3, *B*). The distribution showed that 56% of the CBCT buccal bone thickness measurements were greater than the corresponding direct measurements, and 41% were smaller. There also did not appear to be any relationship between the magnitude or direction of the difference between CBCT and direct measures and the average of direct and CBCT buccal bone thickness measurements. The mean absolute difference between methods was 0.13 ± 0.12 mm, and both concordance and Pearson correlation coefficients were 0.86. The 2-tailed paired *t* test demonstrated no significant difference between CBCT and direct buccal bone thickness measurements.

DISCUSSION

The aim of this study was to determine the reliability and accuracy of buccal bone height and buccal bone thickness measurements made from CBCT images. Because direct measurements were used as our standard from which to evaluate overall CBCT accuracy and reliability, it was important to have extremely high confidence in the direct measurement values. We found that the mean absolute differences and standard deviations between the 2 raters' direct measurements were less than 0.1 mm for both buccal bone height and buccal bone thickness, with concordance correlation coefficient values of almost 1.00 and 0.98, respectively. These indexes showing excellent interrater agreement support the appropriateness of the direct measurement technique used, creating a reliable standard from which to judge the CBCT measurements.

Repeated CBCT measurements by 2 investigators allowed assessment of both intrarater and interrater reliabilities. For intrarater reliability, timing of the measurement was found to contribute 0.3% or less to the overall variance of the data. Of the previous studies investigating CBCT measurements, several have reported on intrarater reliability, including investigations of dental measurements,[22] alveolar bone height[26] and thickness,[27] root length,[19] and cross-sectional dimensions of the mandible and mandibular canal.[28] These studies found intraclass correlation coefficients ranging from 0.93 to 0.99, thus also showing excellent reliability. As for interrater reliability, our CBCT values showed an average absolute difference equivalent to 1 voxel (0.30 mm) for buccal bone height and less than half a voxel (0.12 mm) for buccal bone thickness. Only a few previous studies have used multiple examiners to analyze interrater reliability with CBCT measurements. Suomalainen et al[29] demonstrated an almost perfect association with intraclass correlations of 0.999 between raters for cross-sectional height and thickness measurements of mandibles, and Kamburoğlu et al[28] reported intraclass coefficients from 0.84 to 0.97 when measuring the same mandibular dimensions using the mandibular canal as a landmark. More recently, Sun et al[27] demonstrated intraclass correlation ranges of 0.73 to 0.90 and 0.83 to 0.92 for buccal bone height and buccal bone thickness, respectively, across multiple CBCT resolutions of untreated porcine maxillae. In this study, we showed comparable, high interrater reliability with concordance correlation coefficients of 0.98 and 0.90 for

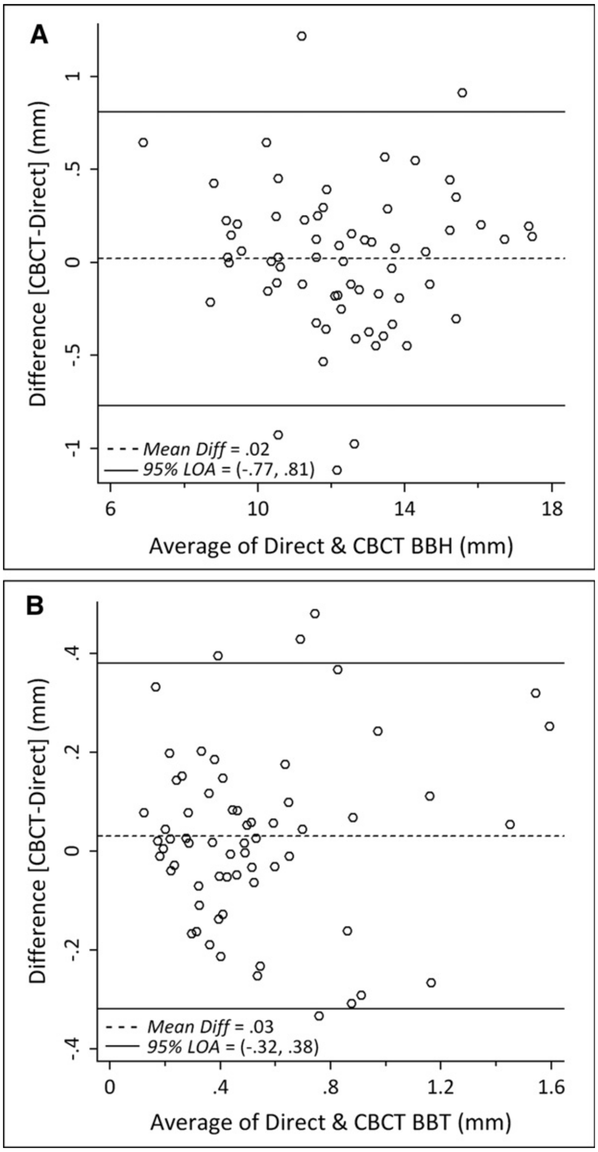


Fig 3. Bland-Altman plots portraying the agreement between direct and CBCT measurements for **A,** buccal bone height and **B,** buccal bone thickness. Each *circle* represents the difference between a CBCT-derived measurement value and a direct measurement value (*y-axis*), relative to the average of the direct and CBCT values (*x-axis*). The *dashed lines* indicate the mean difference (*Diff*), and the *solid lines* show the 95% limits of agreement (*LOA*).

buccal bone height and buccal bone thickness measurements, respectively.

Assessment of overall buccal bone height and buccal bone thickness measurement accuracy showed that the mean differences between direct and CBCT measurements were nearly zero, with no significant trend to either underestimate or overestimate the linear distances. When the absolute difference was taken into account for each direct vs CBCT measurement, the mean absolute differences were 0.30 mm for buccal bone height and 0.13 mm for buccal bone thickness. The concordance correlation coefficient of 0.98 for buccal bone height was high, indicating strong agreement between direct and CBCT measurements. The concordance correlation coefficient of 0.86 for buccal bone thickness demonstrated good agreement, although not as strong as for buccal bone height. Previous studies with radiographic images acquired from CBCT scans to measure linear distances in the maxillomandibular region have demonstrated comparable accuracy. Mischkowski et al[30] reported a mean absolute difference of 0.26 mm (±0.18) for comparing direct and CBCT measurements of the distances between artificial landmarks created on the maxilla and the mandible. Stratemann et al[31] tested the accuracy of 2 CBCT units and found mean absolute errors of 0.07 ± 0.41 mm and 0.00 ± 0.22 mm for various craniofacial distances. Using mean error, Loubele et al[32] found that CBCT imaging underestimated the buccolingual thickness of mandibles by an average of 0.23 ± 0.49 mm. However, all these studies used dry skulls in addition to radiopaque markers to aid in landmark identification.

CBCT studies relying on landmark identification without markers and where soft tissue was present have shown similar mean accuracy values, but with larger standard deviations. Compared with direct measurements, Sherrard et al[19] reported mean differences of less than 0.15 and 0.30 mm for measurements of overall tooth and root lengths, respectively, when imaging porcine heads. However, standard deviations ranged from ±0.93 to ±1.17 mm for overall tooth lengths and from ±1.71 to ±1.83 mm for root lengths. Grimard et al[33] found mean differences of 0.1 mm or less when measuring human periodontal defects on CBCT images compared with direct measurements obtained after reflection of full-thickness flaps, with standard deviations of 0.7 to 1.2 mm, depending on the timing and the landmarks selected. Our values for mean differences and mean absolute differences of ≤0.13 mm for buccal bone thickness and ≤0.30 mm for buccal bone height are comparable with the findings of these studies, whereas our standard deviations (≤0.40 mm) are more similar to the results from dry skull studies with landmark identifiers. It may be that our standardized protocol and choice of landmarks allowed for more consistent identification of points of interest, decreasing the variability of repeated measurements. For example, choosing a highly contrasting landmark such as the incisal edge (or the buccal cusp tip) with a border of enamel and air would make identification more consistent than attempting to identify structures at the junction of tissues with similar radiodensities, such as the cementoenamel junction or the root apex. In addition, patient movement during scan acquisition could negatively impact the variances reported in clinical studies.

When measuring maxillofacial structures that have relatively small dimensions, an important consideration is the distinction between measurement accuracy and spatial resolution (the ability to differentiate between 2 objects in close proximity). Molen[34] suggested reporting a CBCT scan's spatial resolution in addition to voxel size because, although many studies have reported linear accuracy to tenths of a millimeter or less (studies cited in the 2 paragraphs above), investigations of spatial resolution report values significantly greater than the voxel sizes. Although spatial resolution equal to the voxel size should be achievable in theory, this has not been the case in practice because of noise and other factors such as scatter. For example, Ballrick et al[35] acquired i-CAT images of custom radiographic phantoms and, through varied spacing of pairs of metal wires, found that the spatial resolution was 0.84 mm for scans equivalent to the imaging parameters used in our study. When attempting to distinguish the wire pairs as only patterns and not as separate entities, they found that the minimum distance required decreased to 0.68 mm. In the same study, the mean absolute error for linear measurements between chromium markers was less than 0.07 ± 0.05 mm.[35] By comparison, our mean absolute errors were appreciably greater for buccal bone height (0.30 ± 0.27 mm) and buccal bone thickness (0.13 ± 0.12 mm). The increased error can most likely be attributed to soft-tissue interference and the lack of radiopaque markers. Also with regard to this study, measurements of buccal bone thickness (0.54 ± 0.35 mm) often relied on identifying landmarks of similar radiodensity located closer together than the reported scan resolution limit of 0.84 mm mentioned above.[35] Nevertheless, the small mean absolute error (0.13 mm) and the solid concordance correlation coefficient (0.86) suggest that the measurements were made with reasonably good accuracy and consistency. These findings can be explained by the analogy of estimating the last digit of a distance within the finest markings of a ruler or probe since, as Ballrick et al[35] have acknowledged, even though an image "is not perfectly clear, it can still adequately represent the structures and be of diagnostic value." Likewise, the higher concordance correlation coefficient for buccal bone height measurements (0.98) might relate to the magnitude of the measurements (12.34 ± 2.21 mm) largely exceeding the spatial resolution of the scans. This phenomenon, in addition to the superior interrater reliability, tends to favor buccal bone height over buccal bone thickness measurements for quantitatively investigating the effects of orthodontic therapy on buccal alveolar bone.

By using Bland and Altman's limits of agreement, one would expect that 95% of the differences between CBCT images obtained with the settings used in this study and direct measurements would be between −0.77 and 0.81 mm for buccal bone height and between −0.32 and 0.38 mm for buccal bone thickness. A consideration related to these findings is that our values were computed based on the pooled data of 3 repeated measurements and 2 raters; thus, the average values might represent a narrower result than what would be expected if only 1 measurement had been taken, as is often done in clinical assessments of patients. However, based on the generalizability analysis, the variability in measurements attributable to repeated measures and raters was extremely small relative to other sources; thus, the increase in reliability from pooling the estimates vs using 1 estimate at random is minimal. When weighing the clinical relevance of the findings based on clinical studies relying on CBCT measurements, the 95% limits of agreement and the Bland-Altman plot of the pattern of differences between the direct and CBCT measurements across the average values of the measurements should be considered in addition to the statistical test of the mean difference. For example, alveolar bone with a thickness below the threshold of 0.4 mm could have an increased risk of misdiagnosis as either a fenestration or a dehiscence. Using dry skulls to examine the accuracy and reliability of detecting naturally occurring alveolar bony defects, Leung et al[26] found a high false-positive rate, with 3 times the number of defects detected on CBCT images compared with direct examination. In addition, decreased buccal bone thickness can negatively affect the accuracy of buccal bone height measurements, as shown by Sun et al.[27] They demonstrated underestimation of buccal bone height by 0.9 to 1.2 mm when buccal bone thickness was artificially thinned to levels near or below the 0.4 mm voxel size of the CBCT scan.

A relatively unique aspect of our study was that it was conducted with multiple cadavers. This approach was selected to more closely replicate clinical CBCT investigations relative to previous studies that have largely been based on radiographic phantoms[35] or dry skulls[30-32] with an artificial substitute for soft-tissue interference. Moreover, previous CBCT studies of alveolar bones have relied on data from dry skulls without soft-tissue interference.[26,27] The use of dry skulls might affect the translation of laboratory findings to clinical applications, since research has suggested that soft tissues negatively affect the diagnostic image quality of CBCT scans through increased beam attenuation and radiation scatter.[36] Although it is an improvement in study design, the use of cadavers has limitations with regard to translation to clinical orthodontic practice. The mean age of our subjects was 77 years, which is much older than a typical orthodontic patient. With advancing age, decreased bone density is common, and a corresponding decrease in radiodensity can be detected.[37] The decreased radiodensity would most likely make bony landmark identification more difficult. Another consideration is the effect of embalming on CT images. This has been investigated and found to qualitatively limit image resolution and contrast compared with antemortem scans.[38] This result is similar to what has been found with magnetic resonance imaging, where deterioration of image quality caused by a loss of tissue contrast was observed.[39] Whereas gross anatomic features could be reasonably well interpreted in both studies, further research has been recommended to determine the effect on visualizing microstructures.[39] Another factor that might have contributed to reduced image quality and greater difficulty in landmark identification was the many dental restorations in our subjects. Although our inclusion criteria eliminated measurements along teeth with restorations or adjacent to restored teeth, metallic restorations are known to cause attenuation of the x-ray beams, creating streaking artefacts and lower-intensity imaging through beam hardening.[32,40] Despite these potential hindrances, our results support the accuracy and reliability of CBCT-derived measurements of buccal alveolar bone. Moreover, under more ideal conditions, we would expect to find similar or improved results. A future study to assess these potential limitations could be to compare results from fresh frozen cadavers of various ages.

Final considerations regarding the context of this and other CBCT studies include the wide assortment of commercially available CBCT units, variations in image acquisition settings (eg, image detector type, scan time, field of view, and voxel size) and software settings used when the measurements are made. With regard to the latter variable, bony measurements made in a 3-dimensional volume-rendering mode are subject to the range of radiodensity, often measured in Hounsfield units, that is established by the software or the operator to visualize bone. Too high or too low a threshold would decrease or increase apparent bone mass, respectively, and thereby potentially alter subsequent hard-tissue measurements.[25,26] In addition to operator adjustments of contrast and brightness, measurements made in sectional slices rely on consistent protocols to reproduce the orientation used for direct measurements or to repeat CBCT measurements at different times. With this in mind, one should be cautious in drawing conclusions about the accuracy and reliability of CBCT measurements and when comparing the results of different studies without knowledge of the measurement protocol or the imaging parameters and their potential effects on image distortion and spatial resolution.

CONCLUSIONS

This investigation demonstrated that, under simulated clinical settings, CBCT imaging can provide accurate and reliable representations of buccal alveolar bone dimensions.

1. Comparisons of direct and CBCT measurements repeated by the same investigator after intervals of at least 1 day demonstrated little variance.
2. Comparisons of CBCT measurements made by different investigators had good reproducibility, with greater interrater agreement for CBCT measurements of buccal bone height (0.98) than for buccal bone thickness (0.90).
3. Mean absolute errors between CBCT and direct measurements of buccal bone height and buccal bone thickness were small (0.30 and 0.13 mm, respectively) and showed no statistically significant differences or bias to underestimate or overestimate.
4. The 95% limits of agreement in the submillimeter range were observed for both buccal bone height and buccal bone thickness (between −0.77 and 0.81 mm, and between −0.32 and 0.38 mm, respectively).
5. Overall agreement between CBCT and direct measurements was strong and greater for buccal bone height than for buccal bone thickness, as demonstrated by concordance correlation coefficients of 0.98 and 0.86, respectively.

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