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Accuracy of alveolar bone measurements from cone beam computed tomography acquired using varying settings

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Structured Abstract

Objectives – To investigate the accuracy and reliability of cone beam computed tomography (CBCT) measurements of buccal alveolar bone height (BBH) and thickness (BBT) using custom acquisition settings.
Settings and Sample Population – School of Dentistry, Oregon Health & Science University. Twelve embalmed cadavers.
Materials and Methods – Cadaver heads were imaged by CBCT (i-CAT® 17–19, Imaging Sciences International, Hatfield, PA) using a 'long scan' (LS) setting with 619 projection images, 360° revolution, 26.9 s duration, and 0.2 mm voxel size, and using a 'short scan' (SS) setting with 169 projection images, 180° rotation, 4.8 s duration, and 0.3 mm voxel size. BBH and BBT were measured with 65 teeth, indirectly from CBCT images and directly through dissection. Comparisons were assessed using paired *t*-tests ($p \leq 0.05$). Level of agreement was assessed by concordance correlation coefficients, Pearson's correlation coefficients, and Bland–Altman plots.
Results – Mean differences in measurements compared to direct measurements were as follows, LS 0.17 ± 0.12 (BBH) and 0.10 ± 0.07 mm (BBT), and SS 0.41 ± 0.32 (BBH) and 0.12 ± 0.11 mm (BBT). No statistical differences were found with any of BBH or BBT measurements. Correlation coefficients and Bland–Altman plots showed agreement was high between direct and indirect measurement methods, although agreement was stronger for measurements of BBH than BBT.
Conclusions – Compared to the LS, the similarity in results with the reduced scan times and hence reduced effective radiation dose, favors use of shorter scans, unless other purposes for higher resolution imaging can be defined.

Key words: alveolar bone height; cone beam computed tomography; orthodontics; reliability of results

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Introduction

Use of cone beam computed tomography (CBCT) in dentistry has become increasingly common for diagnosis and treatment planning. CBCT allows the acquisition of two-dimensional planar projections and three-dimensional (3D) volume renderings of the dental arches and surrounding tissues with submillimeter spatial resolution (1), using a comparatively low radiation dose relative to conventional or medical CT (2). Nevertheless for various applications in dentistry, optimal acquisition settings have yet to be fully explored. With regard to orthodontic treatment, dentists are interested in accurate characterizations of alveolar bone both pre-treatment and associated with tooth movement (3, 4). Changes in periodontal support immediately post-treatment may not be detectable through clinical assessments (5), whereas CBCT technology may be ideal for such diagnostic and prognostic evaluations.

Protocols for CBCT imaging involve multiple acquisition settings that influence image quality and effective radiation dose, such as number of projection images (6), size of the field of view (FOV), duration of the scan, and voxel size (7). Default settings accompany CBCT units and these can be manually changed for particular needs including image resolution and size of the area of interest (8, 9). Because CBCT acquires multiple single projection images (i.e., projection data) from which 3D images are reconstructed, the number of projection images is directly related to scan time, resolution and effective radiation dose. Considering that image quality and effective dose are proportional (10), a best practice should be adherence to 'as low as reasonably achievable' (ALARA) principle of radiation exposure (11, 12).

The purpose of this investigation was to compare the linear measurement accuracy of CBCT for assessing buccal alveolar bone height (BBH) and thickness (BBT) under simulated clinical conditions using cadavers where the images were acquired using two disparate acquisition settings impacting the number of projection images, scan duration, and voxel size. This study is based in part on a previous investigation where CBCT acquisition settings bracketed the default settings used by Timock et al. (9).

Material and methods

Sample selection

Sample selection, measurement methods and data analysis mirror the approaches used in our previous investigation (9). Briefly, following review of the study's protocol by the Oregon Health & Science University Institutional Review Board, 17 human cadavers were accessed through the Department of Integrative Biosciences. An initial screening was conducted to insure a periodontium free of damage, and sample and adjacent teeth free of alloy restorations. The criteria were met by five female and seven male cadavers of Caucasian race with a mean age of 77 years. A sample of 65 teeth was selected by direct observation including 48 anterior and 17 posterior teeth (9).

CBCT acquisition

The cadavers' heads were scanned by CBCT (i-CAT® 17–19, Imaging Sciences International, Hatfield, PA, USA) using two custom acquisition settings. The two settings flanked the CBCT default acquisition settings ('DS') used by Timock et al. (9). The DS entailed 309 projection images, made in a 360° arc of rotation, resulting in a scan of 8.9 s duration and 0.3 mm voxel size (9). In this study, one scan had settings with a greater number of projection images, called 'long scan' ('LS'), that is, 619 images, 360° rotation, 26.9 s duration, and 0.2 mm voxel size. A second scan had a lesser number of images called 'short scan' ('SS'), that is, 169 images, 180° rotation, 4.8 s duration, and 0.3 mm voxel size (Table 1). The settings were selected to span a spectrum of adjustable parameters impacting image resolution and effective radiation dose.

Table 1. **i-CAT® 17–19† image acquisition parameters for long, default‡, and short scans**

Technical parameter	Value (long scan)	Value (default scan‡)	Value (short scan)
X-ray source voltage	120 KVp	120 KVp	120 KVp
X-ray source current	5 mA	5 mA	5 mA
Focal spot size	0.5 mm	0.5 mm	0.5 mm
X-ray beam size	23.8 cm × 5 to 19.2 cm	23.8 cm × 5 to 19.2 cm	23.8 cm × 5–19.2 cm
Scanning time	26.9 s	8.9 s	4.8 s
Total no. of pulses	619 images	309 images	169 images
Acquisition rotation	360°	360°	180°
Image detector	Amorphous silicon flat panel	Amorphous silicon flat panel	Amorphous silicon flat panel
Gray scale	14-bit	14-bit	14-bit
Field of view	8 cm	13 cm	13 cm
Voxel size	0.2 mm	0.3 mm	0.3 mm

†Manufacturer: Imaging Sciences International, Hatfield, PA, USA.
‡Default scan parameters from Timock et al. (9).

Direct measurements

As previously reported (9), after completion of the CBCT scans the gingiva was dissected away around each tooth of interest. BBH measurements were made using a digital caliper (General Tools, New York, NY, USA) with a reading to the nearest 0.01 mm. BBH was defined as the linear distance from the most coronal point of the tooth's crown to the buccal alveolar crest along the long axis of the tooth. Buccal bone thickness (BBT) was defined as the linear distance from the cementum of the tooth's root to the lateral surface of the buccal alveolar bone located 3.0 mm apical to the alveolar crest. Following dissection of buccal alveolar bone to approximately 3.0 mm apical to the alveolar crest, BBT measurement was obtained with a modified depth gauge accurate to the nearest 0.01 mm.

Direct measurements were made by two investigators where each made three independent measurements, with a minimum interval of 1 day between measurements (9). The mean direct measurements from both raters served as control datasets for comparison to CBCT data. To document the site where direct BBT measurements were taken, the investigators measured the height from the tooth's cusp tip to the apical base of the dissection site. This measurement was cross-referenced to determine the location where measurements of BBT were taken in CBCT images (9).

CBCT measurements

DICOM files were imported into Dolphin 3D Imaging (Dolphin Imaging Systems, Chatsworth, CA, USA). For the LS and SS, three separate CBCT measurements of BBH and BBT were made for each tooth by a single investigator, with a minimum interval of 1 day between recordings. The measurements were made from slices 0.5 mm in thickness oriented using a step-by-step protocol to digitally replicate the direct measurements, as previously described in detail (9). In CBCT slices, BBH was measured in the sagittal plane (Fig. 1) and BBT in the axial plane (Fig. 2), replicating landmarks used in making direct measurements.

Statistical analysis

MedCalc (version 11.6.1.0, MedCalc Software bvba, Mariakerke, Belgium) was used to calculate intrarater reliability of BBH and BBT measurements made both directly (9), and from CBCT images. Data from repeated measurements were pooled to calculate mean differences and mean absolute differences (positive or negative signs ignored). MedCalc was also used to

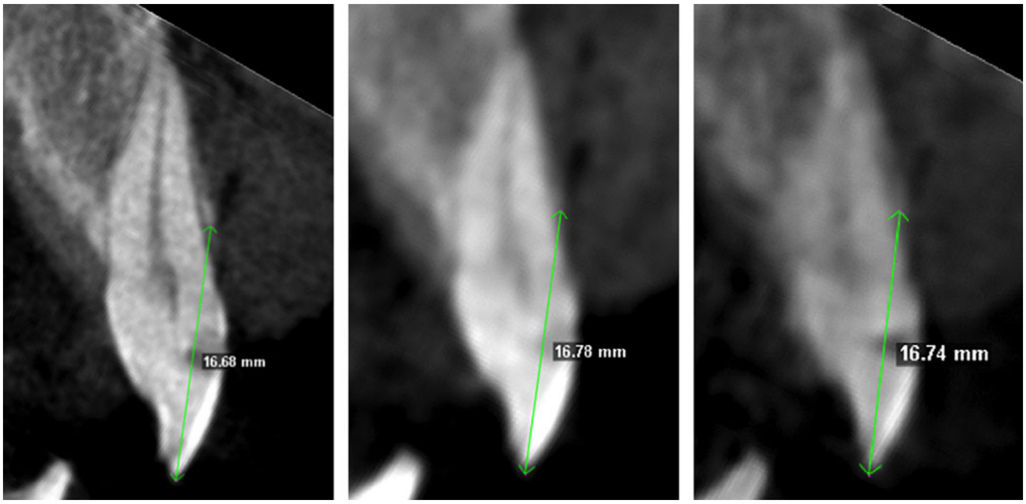

Fig. 1. Example of buccal alveolar bone height (BBH) measurement from cone beam computed tomography (CBCT) sections using long scan (left), default scan (9; center), and short scan (right) CBCT acquisition settings.

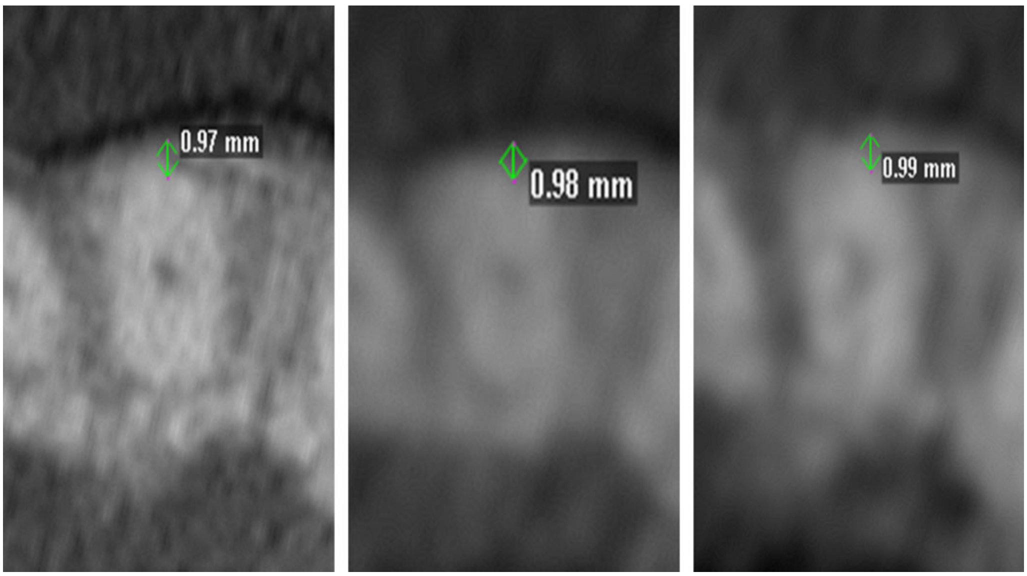

Fig. 2. Example of buccal bone thickness (BBT) measurement from cone beam computed tomography (CBCT) sections using long scan (left), default scan (9; center), and short scan (right) CBCT acquisition settings.

calculate concordance correlation coefficients (CCC) and Pearson's correlation coefficients (PCC) between direct and CBCT measurements.

Comparisons of means, mean differences, and mean absolute differences between measurements from the direct and CBCT measurements from each setting were made using 2-tailed paired *t*-tests; p values <0.05 were considered statistically significant. Agreement between measurements made directly and from CBCT images was assessed with Bland–Altman plots using 95% limits of agreement (LOA; 13).

Results

Direct measurements

Mean absolute differences and standard deviations between the two raters' direct measurements were ≤0.08 mm, while the CCC and PCC were ≥0.98 for BBH and BBT (9).

CBCT measurements

For BBH, measurements from both LS and SS were very similar to direct measurements:

LS = 12.34 ± 2.20, SS = 12.32 ± 2.05 vs. direct = 12.32 ± 2.22 mm (9). The mean absolute difference for LS and SS was 0.17 ± 0.12 mm and 0.41 ± 0.32 mm, respectively. *T*-tests showed no significant difference between direct and LS or SS measurements (Tables 2 and 3). Agreement between LS and SS settings and direct measurements was very strong, with CCC and PCC ≥ 0.97. The Bland–Altman 95% LOA was −0.43 to 0.40 mm for LS and −1.02 to 1.03 mm for SS (Fig. 3).

For BBT, measurements from both LS and SS had means and standard deviations comparable to direct measurements (direct = 0.52 ± 0.33 mm (9), LS = 0.52 ± 0.33, SS = 0.57 ± 0.33). The mean absolute difference for LS and SS was 0.10 ± 0.07 mm and 0.12 ± 0.11 mm, respectively. *T*-tests showed no significant difference in between direct and LS or SS measurements (Tables 2 and 3). Agreement between LS and SS settings and direct measurements was strong, with CCC and PCC ≥ 0.88. The Bland–Altman 95% LOA was −0.25 to 0.24 mm for LS and −0.37 to 0.28 mm for SS (Fig. 4).

Reliability of measurements

Intrarater reliability was very high for all measurements made from LS and SS (CCC ≥ 0.93), except for BBT SS (CCC = 0.88). Agreement between the measurement methods was higher for measurements of BBH than BBT as demonstrated by CCC's (BBH: LS = 0.99, SS = 0.97; BBT: LS = 0.94, SS = 0.88; Table 3).

Discussion

This study investigated the accuracy and reliability of measurements of BBH and BBT from CBCT images, acquired with two disparate acquisitioning settings, compared to direct measurements made through dissections. We previously demonstrated that with our protocol, direct

Table 2. **Measurement accuracy of buccal alveolar bone height (BBH) and Buccal bone thickness (BBT) comparing direct vs. long, default[†], and short scan methods**

Variable	BBH (mm) Mean abs. Diff ± SD*	BBT (mm) Mean abs. Diff ± SD*	BBH CCC (95% CI)	BBT CCC (95% CI)
Direct[†]	0.08 ± 0.06	0.05 ± 0.04	0.999	0.984
Long scan	0.17 ± 0.12	0.10 ± 0.07	0.995 (0.992, 0.997)	0.935 (0.896, 0.960)
Default scan[†]	0.30 ± 0.27	0.13 ± 0.12	0.984 (0.973, 0.992)	0.859 (0.779, 0.912)
Short scan	0.41 ± 0.32	0.12 ± 0.11	0.970 (0.953, 0.981)	0.876 (0.805, 0.922)

[†]Data from Timock et al. (9).
*Paired *t*-test showed no difference in measurements comparing from direct to each scan ($p < 0.05$).

Table 3. **Measurement accuracy of BBH and BBT: Direct[†] vs. long, default[†], and short scan methods**

Variable	BBH (mm) Mean ± SD*	BBT (mm) Mean ± SD *	BBH Mean Diff ± SD*	BBT Mean Diff ± SD*	BBH PCC	BBT PCC
Direct[†]	12.32 ± 2.22	0.52 ± 0.33	0.01 ± 0.10	0.01 ± 0.06	0.999	0.986
Long scan	12.34 ± 2.20	0.52 ± 0.33	−0.02 ± 0.21	0.00 ± 0.12	0.995	0.935
Default scan[†]	12.34 ± 2.21	0.54 ± 0.35	0.02 ± 0.40	0.03 ± 0.18	0.98	0.909
Short scan	12.34 ± 2.05	0.57 ± 0.33	0.00 ± 0.52	−0.04 ± 0.16	0.973	0.883

[†]Data for direct measurements and default CBCT settings from Timock et al. (9).
**T*-test results for buccal alveolar bone height (BBH) and buccal bone thickness (BBT) show that all variables statistically similar ($p < 0.05$).

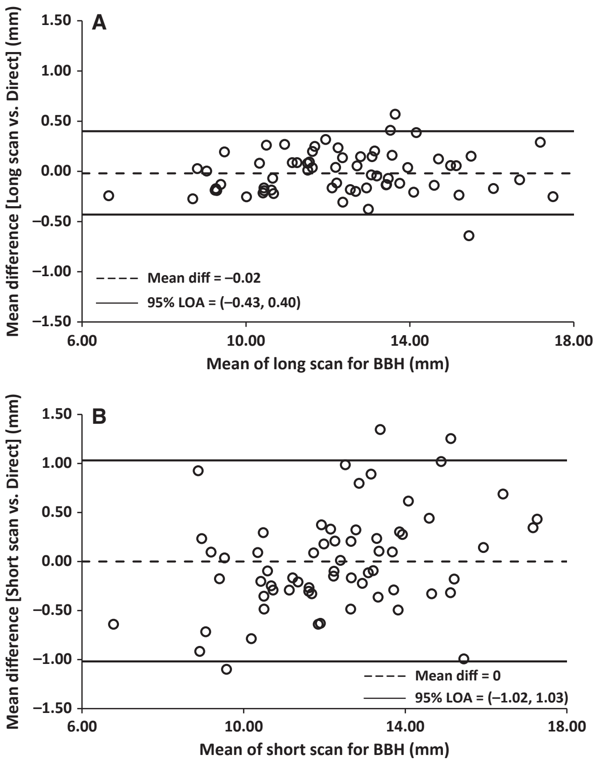

Fig. 3. Bland–Altman plots portraying agreement for buccal alveolar bone height (BBH) between direct and cone beam computed tomography (CBCT) measurements: long scan (A); short scan (B). Circles represent the difference between direct and CBCT measurements (*y*-axis) relative to the average of the direct and CBCT measurements (*x*-axis). The dashed line indicates the mean difference between direct and CBCT measurements; solid line shows the 95% limits of agreement (LOA).

measurements have very high concordance correlation coefficients, justifying use as a control from which CBCT measurements can be evaluated (9).

A number of studies have assessed CBCT's measurement accuracy within the oral maxillofacial region using various measurement protocols, acquisition parameters, CBCT units, and research objectives. For assessments of alveolar bone, investigators have used phantom modules (1, 14, 15), porcine heads (16) and maxillae (17), bovine ribs (18), dry human heads (19–21), maxillae (22) and mandibles (23, 24), embalmed human cadaver heads (9, 25–30), and fresh frozen human cadaver heads (5). The majority of the studies, including the current one, support the accuracy and reliability of measurements of alveolar bone derived from CBCT and the appropriateness of CBCT for use in clinical studies investigating alveolar bone morphology (1, 5, 9, 15–17, 19, 21–26, 29, 30). In the current study, results calculated from the means of three repeat measurements from images of the two CBCT settings had accuracies that did not differ statistically, but did demonstrate variability up to 1.03 mm for BBH with the 95% level of agreement shown by Bland–Altman plots. This finding supports the need for repeated measurements in obtaining optimal precision and accuracy during research and clinical measurements of alveolar bone height and thickness.

In previous studies, Brown and associates imaged dried skulls with variable CBCT settings and compared linear measurement accuracy of cephalometric landmarks relative to direct measurement (6). Using scans involving 153, 306, and 612 projections, they found no statistical difference in measurement accuracy among the three settings (mean differences: 0.44, 0.38, and 0.32 mm, respectively) and suggested a 75% reduction in effective dose with 153 relative to 612 projection scans. Lennon and associates (31) and Durack et al. (32) when investigating detection of artificial dental periapical lesions found comparable results when comparing scans with a reduced arc (180°) vs. a complete arc of rotation (360°). The above findings related to the number of projection images and voxel size, are consistent with other investigations and findings of the current study, that voxel size alone had little effect on standard deviation and linear measurement accuracy (16, 27, 33, 34).

In consideration of the ALARA principle, in the current study the SS (180°; 169 projections) likely reduced effective radiation dose by 73% compared to LS (360°; 619 projections), while demonstrating little compromise in measurement accuracy relative to direct measurements. In a study of CBCT variables that impact effective dose, Pauwels et al. (2) investigated 14 CBCT units and the impact of varying acquisition settings including FOV, tube output, and exposure factors. They found that for most CBCT devices using default settings the effective dose was in the range of 20–100 μSv, with a broader range of 19–368 μSv, or a 20-fold difference depending upon the device and acquisition parameters (2).

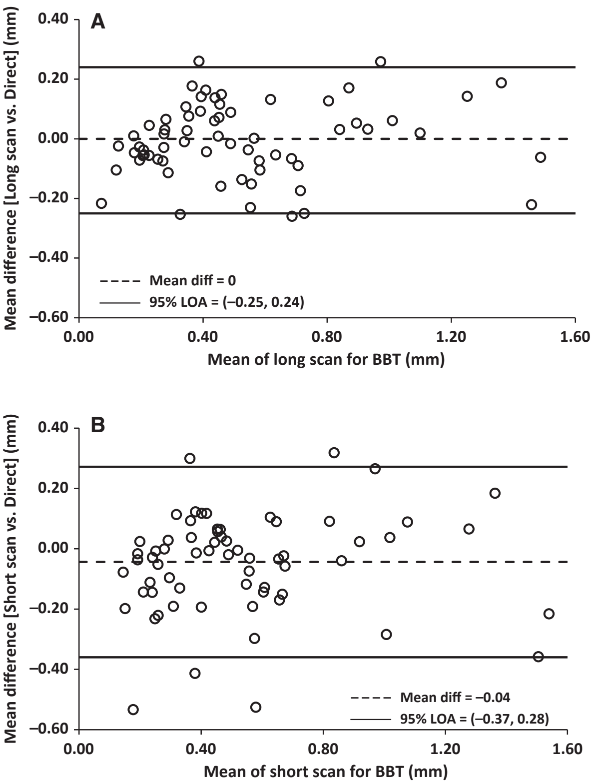

Fig. 4. Bland–Altman plots portraying agreement for buccal bone thickness (BBT) between direct and cone beam computed tomography (CBCT) measurements: long scan (A); short scan (B). See Fig. 3 for details.

The greatest variation in effective dose resulted from changes in the size of the FOV (2). Collimation abilities, such as might be employed to visualize impacted canines, can produce substantial reductions in effective doses (e.g., 90%) when coupled with low-resolution settings relative to full field of view images acquired with default CBCT settings (35). Such findings speak to the need for a balance between diagnostic needs and radiation exposure to optimize imaging strategies for specific assessments (36).

Regarding reliability of measuring BBH vs. BBT, correlation analyses in the current study show more favorable results using BBH with either LS or SS settings, a finding we previously demonstrated when default settings were used (9). Other justification for the use of BBH over BBT in CBCT studies comes from research concerning periodontal tissue biotypes. In study involving 22 cadavers, Fu et al. (5) found only a low to moderate correlation ($R = 0.43$) between gingival recession and BBT, and no association between gingival recession and labial gingival thickness. This result suggests that even if reductions in BBT occur, this may have little correlation to gingival recession as individuals with reduced alveolar bone thicknesses can maintain a healthy attachment apparatus (5). Justification for the use of BBH over BBT also relates to landmark identification, where greater accuracy is achievable with the use of high-contrast structures (9, 20, 25, 26, 28). For BBH, the landmarks are based on the incisal edge or cusp tip at an enamel–airspace interface, and on the interface between alveolar crest of cortical bone and gingival soft tissue, landmarks having high-contrast resolution interfaces. In comparison, BBT measurements involve a landmark distinguishing between cementum and bone, tissues with similar radiodensities on account of their similar hydroxyapatite content, that is, cementum 45–50%; bone 65% (37). Thus, advantages related to landmark identification strongly favor BBH measurements.

A limitation of the current investigation is that while the results show it is possible to accurately measure very thin alveolar bone, the data did not address the specificity or sensitivity of CBCT for the detection of bony dehiscences or fenestrations because such conditions were not recorded during dissection. Leung and associates investigated the diagnostic ability of CBCT to detect dehiscences and fenestrations with dried skulls and showed high negative predictive values, that is, specificity, for both, and only modest sensitivity in the detection of dehiscences (20). More recently, Patcas et al. (30) with a cadaver study of lower incisors found a tendency for CBCT to show false-positive detections of root fenestrations. To have improved the current study, independent, blinded raters unfamiliar with the sample inclusion criterion could have applied our BBH and BBT measurement protocols to determine the negative and positive predictive values for such bony defects.

Ex vivo research as used the current study closely approximates clinical conditions and indicates that CBCT can accurately and reliably measure alveolar bone to a clinically relevant level. While a number of *in vivo* CBCT studies have made measurements of alveolar cortical bone (3, 4, 38, 39), few have compared their CBCT measurements to direct measurements (5, 30). *In vivo* studies comparing CBCT and direct measurements should be conducted to demonstrate accuracy and reliability under clinical conditions, such as the impact of patient motion during image acquisition. A potential next step could investigate in live human subjects who have undergone CBCT imaging and are planned for therapeutic reasons to have full thickness mucoperiosteal flap surgical procedures where direct BBH measurements could be obtained during surgery. In addition, for longitudinal assessments of alveolar bone morphological accompanying orthodontic treatment, use of CBCT tooth-based superimposition protocols may improve the reliability of measurements (40).

Overall, a clinically important finding of our investigations is there was no statistical difference in accuracy between measurements obtained from scans made with widely varying numbers of projection images. For research using non-living subjects and applications requiring high precision, higher resolution CBCT parameters, producing increased quantities of projection data, may be indicated as shown by the reduced mean absolute differences and tighter confidence intervals for LS vs. SS settings. With patients, our results and that of others (1, 30) suggest that imaging protocols involving fewer projection images do not lower linear measurement accuracy and potentially achieve significant reductions in effective radiation dose.

Conclusions

1. CBCT imaging can provide comparably accurate and reliable characterization of buccal alveolar bone dimensions using either of two diverse acquisition settings including 619 vs. 169 projection images, 360° vs. 180° arcs of rotation, 26.9 s vs. 4.8 s scan time, and 0.2 mm vs. 0.3 mm voxel size.
2. When quantifying alveolar bone height and thickness, the similarity in measurement outcomes paired with the desirability of reducing effective radiation dose should bias CBCT acquisition settings toward scans with a reduced quantity of projection images and overall duration, along with use of repeated measurements.
3. With the scan acquisition settings assessed, relative to direct measurements BBH demonstrated stronger agreement than did BBT.

Clinical relevance

Assessments of alveolar bone height and thickness are of potential interest to orthodontists for treatment planning and monitoring treatment outcomes. CBCT allows for accurate measurement of buccal bone height and thickness when using default acquisition settings. This investigation assessed the accuracy of measurements using CBCT scans with greater and lesser resolution than default settings and found measurement accuracy using the average of three repeat measurements were comparable between high- and low-resolution scans. For patient safety considerations, CBCT settings resulting in lower effective radiation doses would be recommended for assessments of alveolar bone morphology involving linear measurements.

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