Accuracy of alveolar bone measurements from cone beam computed tomography at multiple parameters

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of the requirements for the degree of
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Abstract

Introduction: Cone-beam computed tomography (CBCT) imaging has expanded the potential to analyze alveolar bone morphology in 3 dimensions, but accuracy of the technique has yet to be well defined. To investigate the accuracy and reliability of CBCT measurements, buccal alveolar bone height (BBH) and thickness (BBT) were assessed using 2 acquisition settings. **Methods:** 12 embalmed human cadaver heads were scanned twice with an i-CAT® 17-19 unit (Imaging Sciences International, Hatfield, PA), once (long scan) using 0.2 mm voxel-size, 26.9 s scan, and 360° revolution, and again (short scan) using 0.3 mm, 4.8 s, and 180°. BBH and BBT measurements associated with 65 teeth were made at standardized locations in radiographic sections consistently oriented through use of a detailed protocol. Each measurement was repeated at 3 separate occasions and compared to direct measurements obtained through dissection. Measurements made from the 2 settings were compared by two tailed *t* tests ($p \leq 0.05$), and agreement was assessed by concordance correlation coefficients (CCC). **Results:** Mean absolute differences in measurements for long scan were BBH 0.17± 0.12 mm and BBT 0.10 ± 0.07 mm, and for short scan were BBH 0.41±0.32 mm and BBT 0.12±0.11 mm. Comparing the settings, *t* tests showed statistical similarity for all BBH or BBT measurements. With neither setting demonstrating an under- or over-estimation tendency. Agreement between the measurement methods compared to direct measurement was high, although agreement was higher for BBH than BBT as demonstrated by CCC (BBH: A=0.99, B=0.97 vs. BBT: A=0.94, B=0.88). **Conclusions:** Using multiple voxel sizes and scan times, CBCT can be used to accurately and reliably assess BBH and BBT with repeated measurements. Compared to the longer scan times, the similarity in results with the reduced scan time and hence reduced effective radiation dose favors use of shorter scans, unless a purpose for higher resolution imaging can be defined.

INTRODUCTION

In recent years, cone beam computed tomography (CBCT) has become commonly accepted for radiographic diagnosis, treatment planning and follow-up in dentistry. CBCT allows the acquisition of two-dimensional (2D) planar projections and three-dimensional (3D) volume renderings of the dental arches and surrounding tissues with sub-millimeter spatial resolution (i.e., the ability to separate 2 objects in close proximity) [14] and a comparatively low radiation dose compared to conventional CT or medical CT[2]. There are numerous dental applications that benefit from the use of CBCT; however, optimal acquisition settings for each application have yet to be fully explored.

The term CBCT does not refer to a single imaging protocol. There are multiple parameters that influence the quality and effective dose of CBCT imaging, including the number of projection frames or images[18], the size of the field of view (FOV), duration of scan, and the voxel size[3]. These parameters vary between CBCT units and within different imaging protocols of individual CBCT devices. Diagnosticians should select image acquisition parameters on a case specific basis, dependant on the particular application, the desired image quality and the size of the area of interest[1, 9]. Through rotational scanning, CBCT acquires multiple single projection images (i.e., projection data) from which 3D images are reconstructed. In general, the number of projection images is directly related to scan time, resolution and effective radiation doses. Considering that image quality and effective dose are proportional[15] and directly related to the quantity of projection data[18], a best practice should be to follow generally applied, "As Low As Reasonably Achievable" (ALARA), principles of radiation exposure[5, 6] when selecting the appropriate parameters for specific applications.

Among other applications, orthodontists are interested in the accurate characterization of alveolar bone using CBCT because limited ability exists otherwise to observe the acute effects of specific forms of orthodontic tooth movement on the supporting alveolar bone. Changes in bone thickness, height and/

or density invariably accompany orthodontic tooth movement, and such changes may have long-term beneficial or harmful periodontal consequences. These effects may not be immediately observable through clinical assessment of the periodontium[8], and periodontal changes identified as individual's age may be appropriately or inappropriately attributed to previous orthodontic treatment. Advantages inherent to CBCT technology potentially make this an ideal prognostic and diagnostic instrument to evaluate alveolar bone changes associated with orthodontic treatment.

To date, insufficient evidence exists regarding the quality of CBCT depictions of alveolar bone in clinical settings, although many *in vitro* and *ex vivo* inquiries exist that demonstrate the accuracy and reliability of CBCT depictions of alveolar bone[7-13,14,24-26,30, 35,36]. The focus of this investigation was to assess the linear measurement accuracy of CBCT for assessing buccal alveolar bone height (BBH) and thickness (BBT) under simulated clinical conditions when the images were acquired using varying acquisition parameters. Knowledge of CBCT's accuracy at various voxel sizes, scan durations, projection images, and effective radiation doses, should facilitate the judicious prescription of CBCT and help establish a protocol for subsequent *in vivo* analysis of alveolar bone.

MATERIAL AND METHODS

This study was initiated and conducted in conjunction with an analogous inquiry involving CBCT's depiction accuracy of human alveolar bone by Timock et al[9]

Sample selection

Human cadaver specimens were accessed through the Department of Integrative Biosciences, School of Dentistry (obtained from the Oregon Health & Science University Body Donation Program), following review of the study's protocol by the Institutional Review Board. An initial screening of 17 subjects was performed, with 12 dentate cadavers (5 females and 7 males, all Caucasian, with a mean age of 77 years at death) fulfilling the initial selection criteria. A final sample of 65 teeth was selected by direct observation based on the initial selection criteria established by Timock et al[9] (i.e., periodontium free of dissection, damage, pathology, or embalming artifacts and a dentition free of mechanical damage and sample teeth or adjacent teeth free of alloy restorations). Table I shows the distribution of the teeth examined by tooth type.

CBCT acquisition

The cadaver specimens were scanned in a standardized orientation within the CBCT unit (i-CAT® 17-19 CBCT unit; Imaging Sciences International, Hatfield, PA), prior to any dissection or direct measurements, following the CBCT acquisition protocol established by Timock et al[9]. The following image acquisition parameters were used with a, long scan: 0.2 mm voxel size, 26.9 s scan duration, 619 projection frames, and 360° arc of rotation, and a short scan: 0.3 mm, 4.8 s, 169 projections, and 180°. The acquisition parameters used in the current study flanked the commonly accepted default settings used by Timock et al[9] (i.e., henceforth referred to as medium scan[9]) and sought to represent the spectrum of adjustable parameters in terms of image quality and effective radiation doses (see Table II for a detailed list of parameters used in long, medium[9], and short scans).

Direct measurements

After completion of the CBCT scans, the cadaver specimens were dissected using a full thickness mucoperosteal flap reflected around each tooth of interest. Buccal bone height (BBH) measurements were made using a digital Vernier caliper (General Tools, New York, New York) 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 (at the mesiodistal center of the distance between interproximal contact points) to the buccal alveolar crest along the long axis of the tooth (at a point perpendicular to the dental arch-form). In cases of maxillary molar measurements, the mesiobuccal cusp and root were measured (see Timock et al[9]).

Buccal bone thickness (BBT) was defined as the linear distance from the tooth's root cementum to the lateral surface of the buccal alveolar bone at a point approximately 3.0 mm apical to the alveolar crest. Following buccal alveolar bone dissection, direct measurements were obtained with a modified depth gauge, by orienting a depth probe (accurate to the nearest 0.01 mm) parallel to the root surface and perpendicular to the dental arch-form. By selecting landmarks and obtaining measurements in spatial planes perpendicular to the dental arch-form, it eliminates confounding variables resulting from misaligned or rotated teeth for BBH and BBT.

For direct measurements of BBH and BBT, two investigators each made three independent measurements, with a minimum interval of one day between measurements. The mean direct measurements from both raters', served as control data sets for comparison to CBCT data. For BBT, in order to ensure reliable physical and digital landmark identification between CBCT and directly obtained measurements, each investigator measured the height at which the directly obtained BBT values were recorded relative to the coronal reference point, and the average value was cross-referenced during the CBCT measurements.

CBCT measurements

DICOM files were imported into Dolphin 3D Imaging (Dolphin Imaging Systems, Chatsworth, CA) for analysis. Dolphin 3D was selected due to its popularity and wide usage in orthodontics. For the long scan and the short scan, three separate CBCT measurements of BBH and BBT were made by a single investigator for both parameters, with a minimum interval of one day between recordings. The measurements were made in a 0.5 mm sectional slice in a darkened room on 20.1 inch flat panel monitor. A standardized orientation was established, and a step-by-step measurement protocol was followed to digitally replicate the direct measurements, as described in detail by Timock el al[9]. CBCT

BBH measurements were made in the sagittal plane (see Figure I) and BBT in the axial plane (see Figure II) at the aforementioned reference points recorded during direct measurement data collection

Statistical analysis

MedCalc (version 11.6.1.0, MedCalc Software bvba, Mariakerke, Belgium) was used to calculate intrarater reliability within the measurement methods (i.e., BBH and BBT) for direct and CBCT measurements using long and short scan settings. Data from repeated measurements were pooled to described mean differences and mean absolute differences (positive or negative signs ignored), and data was further analyzed by calculating concordance correlation coefficients and Pearson correlation coefficients using MedCalc for six sets of data: direct measurements of BBH and BBT, CBCT measurements of BBH and BBT for long scan and short scan settings. The concordance correlation coefficient, while similar to the Pearson correlation coefficient in measuring the linear relationship, or association, between two sets of data, also takes into account any departure from a line of perfect agreement such as a scale or location shift.

Comparisons of means, mean differences, and mean absolute differences between the direct and each CBCT acquisition parameter and measurement method 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 two 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 using 95% limits of agreement (LOA; average differences +/- 1.96 the standard deviation of the differences).

Average absolute deviations were derived to compare measurement methods of BBH and BBT for accuracy and reliability. This is a measure of central tendency, and provides normalization of data for the comparison of samples of differing means; and represents the relative percent deviation from the mean.

RESULTS

Direct Measurements

Mean absolute differences and standard deviations between the two raters' direct measurements were ≤ 0.08 millimeters for both BBH and BBT, while concordance correlation coefficients and Pearson correlation coefficients were of nearly 1.00 for BBH and 0.98 for BBT (Table III).

Buccal Bone Height (BBH)

BBH, with both long and short settings, had means and standard deviations comparable to direct measurements (direct=12.32 ± 2.22 mm, long scan= 12.34±2.20 mm, short scan=12.32 ± 2.05 mm), with the resulting mean differences close to zero (long scans -0.02 ± 0.21 mm, short scans 0.00± 0.52 mm). Neither setting demonstrated a statistically significant under or overestimation tendency for BBH. Ignoring the sign of the difference between CBCT and direct measurements, the mean absolute difference for long scan BBH and short scan BBH was 0.17± 0.12 mm and 0.41±0.32 mm, respectively (see Tables IV and V; also show comparisons to medium scan[9]).

Analysis of agreement between long and short scan settings and direct measurements for BBH showed concordance and Pearson correlation coefficients ≥ 0.97. The Bland-Altman 95% limits of agreement for long scan BBH were -0.43 mm to 0.40 mm (range of ±0.42 mm) and -1.02 mm to 1.03 mm (range of ± 102mm) for short scan BBH (see Figure III for Bland-Altman plots for BBH).

The Paired two tailed t test demonstrated no significant difference between long scan BBH, short scan BBH, and direct BBH measurements (see Tables IV and V for comparisons to medium scan[9]).

Buccal Bone Thickness (BBT)

BBT, with both long and short scan settings, had means and standard deviations comparable to direct measurements (direct=0.52±0.33 mm, long scan=0.52±0.33 mm, short scan=0.57±0.33 mm), with the resulting mean differences close to zero (long scan 0.00±0.12 mm, short scan -0.04±0.16 mm). Neither setting demonstrated a statistically significant under- nor overestimation for BBT. Ignoring the sign of the difference between CBCT and direct measurements, the mean absolute differences for long scan BBT and short scan BBT was 0.10±0.07 mm and 0.12±0.11 mm, respectively (see Tables IV and V; also show comparisons to medium scan[9]).

Analysis of agreement between both CBCT settings and direct measurements were good, with concordance and Pearson correlation coefficients ≥ 0.88. The Bland-Altman 95% limits of agreement for long scan BBT were -0.25 mm to 0.24 mm (range of ±0.25 mm) and -0.37 mm to 0.28 mm (range of ± 0.33mm) for short scan BBT (see Figure IV for Bland-Altman plots).

The Paired two tailed t test demonstrated no significant difference in BBT between long scan, short scan, and direct measurements (see Tables IV and V; also show comparisons to medium scan[9]).

Comparing BBT and BBH

Intrarater reliability was very high for all measurements of long and short scan (CCC≥ 0.93), except short scan BBT (CCC=0.88). Agreement between the measurement methods for long and short scans, although statistically similar, were higher for measurements of BBH than BBT as demonstrated by CCC's (BBH: long scan=0.99, short scan=0.97 versus BBT: long scan=0.94, short scan=0.88) (see Table IV; also includes values for medium scan[9]).

Average absolute deviations (AAD) of measurements were calculated to compare accuracy and precision of both measurement methods (i.e., BBH and BBT) for characterizing alveolar bone. This measures the relative central tendency of a data set and through data normalization accounts for the fact that the mean direct measured distances for BBH and BBT were significantly different in magnitude (BBH: 12.32 mm ±2.22 and BBT: 0.52 mm ±0.33). BBH demonstrated greater normalized agreement with direct measurements (long scan=1.38% AAD, short scan=3.33% AAD) compared to BBT (long scan=19.23% AAD, short scan=23.08% AAD) (see Table IV; also includes medium scan[9]).

DISCUSSION

The purpose of this study was to investigate the dimensional accuracy and reliability of BBH and BBT measurements from CBCT images obtained at multiple image acquisitioning parameters, when compared to direct measurements. Additionally, we aimed to provide clinical and research recommendations for CBCT acquisition parameters for measurement of buccal alveolar bone.

The CBCT measurements were compared to direct measurements as these continue to be the gold standard from which all other alveolar bone measurement protocols should be judged[24, 25,29,34,35,36,37,38]. The extremely high concordance correlation coefficients obtained for our direct measurements of BBH (0.99) and BBT (0.98) justified their use as a control from which CBCT measurements could be reliably evaluated.

The paired t tests demonstrated no significant difference between long scan, short scan, and direct BBH and BBT measurement methods ($p \leq 0.05$). This study demonstrated that using multiple voxel sizes, scan times, and projection images, CBCT with repeated measurements can be used to accurately and reliably assess BBH and BBT, in the presence of soft tissue attenuation.

Results calculated from the means of 3 repeated measurements for each parameter setting and measurement method showed accuracy with statistical similarity, but demonstrated variability in the width of their 95% confidence intervals. Repeated measurements are highly recommended for precision accuracy during research and clinical measurements of alveolar bone and this approach may minimize reproducibility errors due to standard deviation (see Tables IV and V).

A wide variety of studies have previously assessed CBCT's measurement accuracy within the oral maxillofacial region. Their measurement protocols, acquisition parameters, CBCT manufacturer types, and research objectives are as numerous and varied as the number of studies that exist in alveolar bone-CBCT research. Thus, one should be cautious about the over-generalization of measurement protocols or imaging parameters[9] for the wide array of dental applications.

In an attempt to determine CBCT's measurement accuracy of alveolar bone, investigators have used phantom modules[14, 23, 24], porcine heads[26] and maxillae[25], bovine ribs[27], dry human heads[7,34,36], maxillae[12] and mandibles[13,35], embalmed human cadaver heads[9-11, 28-30], and fresh frozen human cadaver heads[8]. The majority of these studies support the accuracy and reliability of CBCT derived measurements of alveolar bone, at clinically and statistically significant levels, and suggests CBCT's appropriateness for use in human clinical studies dealing with alveolar bone characterization[7-13, 14, 24-26, 30, 35, 36]. Our findings are consistent with previously published research that demonstrates CBCT's accuracy and supports its use for the analysis of human alveolar cortical bone.

A particular focus of this study was to assess CBCT's measurement accuracy of BBH and BBT measurements when the arc of rotation for a particular voxel size was reduced from 360° to 180°. It may be estimated that the dose reduction for a 180° scan, which effectively reduces projection data by nearly half would also half the effective radiation dose. For this study, calculating effective doses from thermoluminescent dosimeter (TLD) chips for long and short scans would have allowed for a more definitive discussion about relative dosimetry. Comparing long scan (619 projections) and short scan (169 projections) in our study, the reduction in resolution and projection data (i.e., short scan) cost very little in terms of measurement accuracy and may presumably reduce effective radiation dose by 73%, considering x-ray pulses/ projections are directly proportional to effective radiation dosages. Having determined spatial resolutions for long and short scans, with a line pair phantom, would have strengthened or diminished the conclusions drawn from measurement accuracy alone, considering spatial resolution and linear measurement accuracy are independent measures. Nonetheless, the statistical similarity between measurement accuracy for long and short scans, under simulated patient conditions, favors reduced arc of rotation or limited projection image scans, given the effective dose reducing possibilities of limited scans. Visually, both settings produced renderings of appropriate clarity for general orthodontic purposes, but long scan settings produced images with somewhat greater definition (see Figures I and II). Whether greater image clarity provides certain diagnostic or prognostic value has yet to be completely determined.

Brown et al[18], using dried skulls, compared linear measurement accuracy of limited projection data CBCT (i-CAT Classic, Imaging Sciences International) measurements of cephalometric landmarks against direct measurement, at three scan settings of different numbers of projections (153, 306, and 612 projections). They found no statistical difference in measurement accuracy between their 3 scan settings (mean difference: 0.44 mm, 0.38 mm, and 0.32 mm, respectively), and likewise suggested a 75% reduction in effective dose with their 153 projection scan, compared to their 612 projection scan. Lennon et al[16] and Durack et al[17] have also demonstrated statistically similar image quality between reduced arc of rotation scans (180°) and complete scans (360°) in the detection of artificial dental periapical lesions.

With parameters facilitating collimation, reduced arc of rotations, variable scan times and projections, it is clear that the term CBCT does not refer to a single imaging protocol. In selecting the appropriate parameters to produce a sufficiently detailed image while minimizing patient radiation exposure, one should consider Pauwels et al[2] effective dose estimations based on 14 CBCT units with variable acquisition settings (FOV size, tube output, and exposure factors). Comparing units and acquisition variables, Pauwels and colleagues[2] demonstrated that for most CBCT devices (at default settings) the effective doses are found in the 20-100 µSv range, with a broader range of 19 to 368 µSv (a 20-fold difference) depending upon the device and acquisition parameters. The greatest variation in effective dose resulted from the size of the FOV[2].

When considering the numerous variables that directly affect image quality and the magnitude of effective radiation dose variation, one should consider primary and secondary efforts to reduce patient exposure. Some CBCT units, have the capability of reducing volume diameter to allow examination of individual arches, posterior or anterior segments, or of sextants of individual arches[21]. Such collimation abilities, such as might be employed during the investigation of an impacted cuspid, may produce substantial reductions in effective doses when coupled with low resolution settings (e.g., 10% of a full field of view image acquired with default CBCT settings)[21]. Additionally, researchers have investigated secondary efforts to reduce patient radiation exposure (e.g., copper filtration[20] and leaded patient eyewear[19]). These complex and variable CBCT imaging protocols demand that operators understand and consider diagnostic and treatment needs when prescribing the appropriate dose optimization strategy for their specific assessment[22].

When determining the appropriate protocol for measuring alveolar bone, one should select the method that has greatest prognostic value and relevance. Agreement between BBH and BBT measurement methods for long and short scans, although statistically similar, were higher for measurements of BBH than BBT, as demonstrated by CCC's and PCC's (see Tables IV and V). CBCT measurements demonstrated greater relative agreement with direct measurements of BBH, when data was normalized (1.38% - 3.33% average absolute deviation from the mean), compared to BBT (19.23% - 23.08% average absolute deviation). Presumably, one may have greater confidence detecting a subtle change in linear dimension, due to BBH's greater measurement precision, between 2 time points with the use of the BBH method of characterization. If the magnitude of change in the linear dimension between 2 timepoints is on average greater than 3%, repeated BBH measurements will likely show a statistical difference between time-points. Contrastingly, a subtle bony change in BBT, less than 19% of its linear dimension, may appear statistically similar between time-points, even with repeated sampling.

Another justification for the use of BBH over BBT in CBCT studies comes from recent evidence from Fu et al[8] concerning periodontal tissue biotypes. They suggest a very mild correlation between gingival recession and BBT and no correlation between gingival recession and labial gingival thickness[8]. This evidence suggests that even if reductions in BBT are observed during treatment, this may have little correlation to gingival recession, or potentially an individual will maintain a healthy attachment apparatus dispite reduced gingival or alveolar bone thickness. With this in mind, increases in BBH (i.e., signifying alveolar bone loss) may be more prognostic for subsequent deleterious periodontal effects upon the attachment apparatus compared to decreases in BBT. Future research could investigate the relationships between various gingival biotypes and assorted effects on the attachment apparatus following reductions BBT or increases in BBH in living subjects.

A third justification for the use of BBH over BBT relates to identification of the structures and interfaces involved in the measurements due to the effects of image contrast resolution. Evidence indicates that greater linear measurement accuracy with CBCT is achievable with the use of high-contrast structures[10, 11, 29, 34]. For BBH, the landmarks forming a line are based on the incisal edge or cusp tip at an enamel-airspace interface and on a distant point at the interface between alveolar crest cortical bone and gingival soft-tissue—both high-contrast resolution interfaces. In comparison for BBT landmarks, one must delineate the interfaces between cementum and bone and between bone and soft tissue, within sub-millimeter sized distances. The radiodensities of cementum and bone are closely related because of their similar hydroxyapatite content (i.e., cementum 45-50% and bone 65%). On the other hand, enamel, has a hydroxyapatite content of about 97% and air spaces are entirely radiolucent[39]. These anatomical features make BBH landmark identification comparatively more reliable than BBT.

Thus, given recent periodontal findings, the reduced relative error (i.e., the ability to detect subtle changes in linear dimension) and the structural advantages of landmark identification with BBH measurements, the latter is strongly favored if a single alveolar bone measurement protocol is to be employed.

Timock et al[9] compared CBCT BBT and BBH measurements from cadavers with a clinically relevant measurement protocol at default settings, ones that would typically be used in an orthodontic practice (i.e., 0.3 mm, 360° arc of rotation, 8.9 s scan, 309 projections). Comparing our findings for BBH, the mean absolute differences for long scan (0.17± 0.12 mm), data from Timock et al[9] (medium scan; 0.30 mm ± 0.27 mm), and short scan (0.41±0.32 mm) were statistically similar to each other and the direct measurements. For BBT, the mean absolute difference for long scan (0.10±0.07 mm), medium scan[9] (0.13 ± 0.12 mm), and short scan (12±0.11 mm) were also statistically similar to each other and the direct measurements (see Tables IV and V). Comparing each setting parameter (long scan, medium scan[9], and short scan) and each measurement method (BBT and BBH) shows that despite being statistical similar, a trend toward greater agreement was observed for BBH over BBT. Data suggest the resultant spectrum of mean absolute differences and CCC variations in the measurement accuracy between these 3 groups, can be attributed to the number of projection images (i.e. 169, 309, and 619 projections) and scan times (i.e. 4.8 s, 8.9 s, and 26. 9 s), rather than voxel sizes (0.3 mm, 0.3 mm, and 0.2 mm). This finding is consistent with those of other investigators who likewise concluded that voxel size alone had little effect on standard deviation and linear measurement accuracy[26,28, 37- 38].

A limitation of the current investigation is that while the results show it is possible to accurately measure very thin alveolar bone, they do not address CBCT's specificity or sensitivity in the detection of bony dehiscences or fenestrations because such diagnoses were not recorded during the direct measurement data collection at the time of dissection. Leung et al[34] investigated CBCT diagnostic ability to detect dehiscences (V-shaped buccal alveolar bone margin defects, with an alveolar bone margin to cementoenamel junction distance greater than 3 mm) and fenestrations (isolated root surface areas denuded of bone, covered only by periosteum and overlying gingival) and showed high negative predictive values (i.e., specificity) for both, but only modest sensitivity in the detection of dehiscenses. To have improved this study, independent, blinded raters unfamiliar with the sample inclusion criterion could have employed our BBH and BBT measurement protocols to determine the negative and positive predictive values of these methods in the detection of dehiscences and fenestrations with CBCT.

Extending the current findings in CBCT alveolar bone linear measurement accuracy, a subsequent methodological step should involve living human subjects undergoing CBCT imaging and full thickness mucoperiosteal flap for surgical reasons where direct BBH measurements could be obtained during surgery. These measurements could then be reliably compared to CBCT-derived measurements at multiple acquisition parameters under clinical conditions. To date, no published research has compared direct alveolar bone measurements, obtained from living human subjects in the presence of unstudied clinical conditions (e.g. patient motion), to CBCT derived measurements.

Ex vivo research, such as the current study, closely approximates clinical conditions and indicates that CBCT can accurately and reliably measure alveolar bone to a clinically relevant level. Interestingly, several *in vivo* CBCT studies have made measurements of alveolar cortical bone[31-33] and teeth[32], but none have compared their CBCT measurements to direct measurements. *In vivo* studies comparing CBCT and direct measurements should demonstrate accuracy and reliability before numerous full-scale clinical studies assume measurement accuracy under clinical conditions, especially considering there are clinical parameters that remain unstudied (e.g. effects of patient motion during image acquisition on measurement accuracy and spatial resolution).

Perhaps the most clinically important finding of our study was that there was no statistical difference in accuracy between measurements obtained from long scan, medium scan[9], short scan, and the direct measurements. For research using non-living subjects and various applications requiring high precision, higher resolution CBCT parameters (producing increased projection data quantity) may be advantageous because of the reduced mean absolute differences and tighter confidence intervals for longer scan settings. In contrast, with the use of live subjects, because of the dramatic effective dose reductions possible through the use of lower resolution scans (fewer projection images) and collimation resulting in no effect on linear measurement accuracy[14], the similarity in results and reduced effective radiation dose favors use of shorter scans and collimated fields of view.

CONCLUSIONS

This investigation demonstrated that under simulated clinical settings, at multiple image acquisition parameters, CBCT imaging can provide accurate and reliable characterization of buccal alveolar bone dimensions.

1. CBCT can be used to quantitatively assess BBH and BBT with accuracy and reliability at multiple voxel sizes (0.2 mm and 0.3 mm), arcs of rotation (360° and 180°), scan times (26.9 s and 4.8 s), and projection images (619 and 169 projections).
2. Given the statistically similarity and reduced effective radiation doses of limited volume scans, unless a purpose for higher resolution imaging can be justified, one should consider

reduced scan durations, reduced quantities of projection images, collimated fields of view and repeated measurements.

3. BBH demonstrated greater agreement with direct measurements and should be the protocol of choice when a single alveolar bone measurement method is employed.

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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	5	6
Posterior Total	4	13	17
Total	20	45	65

Table II. i-CAT® 17-19‡ Technical Image Acquisition Parameters for Long, Medium†, and Short Scans			
Technical Parameter	Value (Long Scan)	Value (Medium 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 X 5 to 19.2 cm	23.8 cm X 5 to 19.2 cm	23.8 cm X 5 to 19.2 cm
Scanning Time	26.9 s	8.9s	4.8 s
Total # 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

† Medium Scan parameters republished with permission from Timock et al[9]

Table III. Direct Measurements (Control)		
Variable	BBH	BBT
Mean Diff ± SD (mm)	0.01 ± 0.10	0.01 ± 0.06
Mean Abs. Diff ± SD (mm)	0.08 ± 0.06	0.05 ± 0.04
CCC	0.999	0.984
PCC	0.999	0.986

Table IV. Measurement Accuracy of BBH and BBT comparing Direct (control) versus Long Scan, Medium Scan†, 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)	BBH Avg Abs. Deviation %	BBT Avg Abs. Deviation %
Direct‡	0.08±0.06	0.05±0.04	0.999	0.984	0.65	9.62
Long Scan	0.17±0.12	0.10±0.07	0.995 (0.992,0.997)	0.935 (0.896,0.960)	1.38	19.23
Medium Scan†	0.30±0.27	0.13±0.12	0.984 (0.973,0.992)	0.859 (0.779,0.912)	2.44	25
Short Scan	0.41±0.32	0.12±0.11	0.97 (0.953,0.981)	0.876 (0.805,0.922)	3.33	23.08

Paired two-tailed t-test results for BBH and BBT show that all variables are statistically similar ($p < 0.05$).

† Data republished with permission from Timock et al[9].

‡ Interrater agreement as demonstrated by mean absolute difference, concordance correlation coefficient, and average absolute deviation.

Table V. Measurement accuracy of BBH and BBT: Direct (control) versus Long Scan, Medium Scan†, 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
Medium 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

Paired two-tailed t-test results for BBH and BBT show that all variables statistically similar ($p < 0.05$).

† Data republished with permission from Timock et al[9].

‡Interrater agreement as demonstrated by mean, mean difference, and pearson correlation coefficient.

Figure 1. CBCT BBH Measurements at Multiple Parameters: **A,** Long Scan; **B,** Medium Scan[9]; **C,** Short Scan.

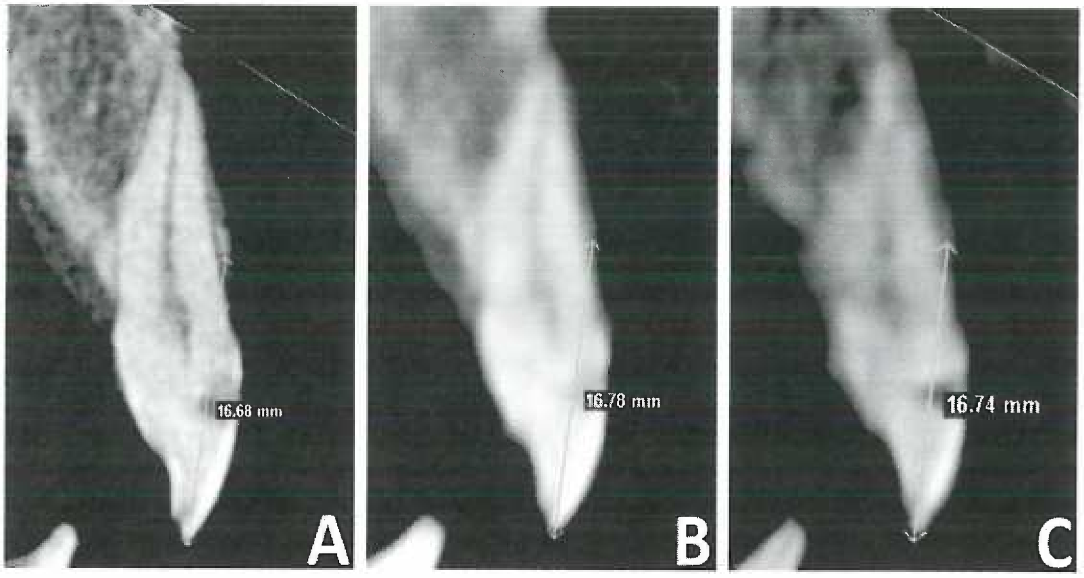


Figure 2. CBCT BBT Measurements at Multiple Parameters: **A,** Long Scan; **B,** Medium Scan[9]; **C,** Short Scan.

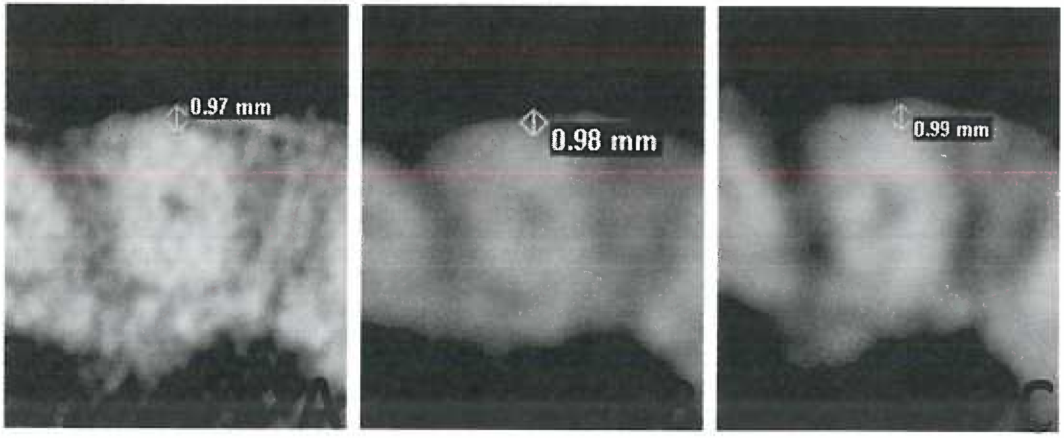


Figure 3. Bland-Altman plots portraying the level of agreement between direct BBH and CBCT measurements: **A,** Long Scan; **B,** Short Scan.

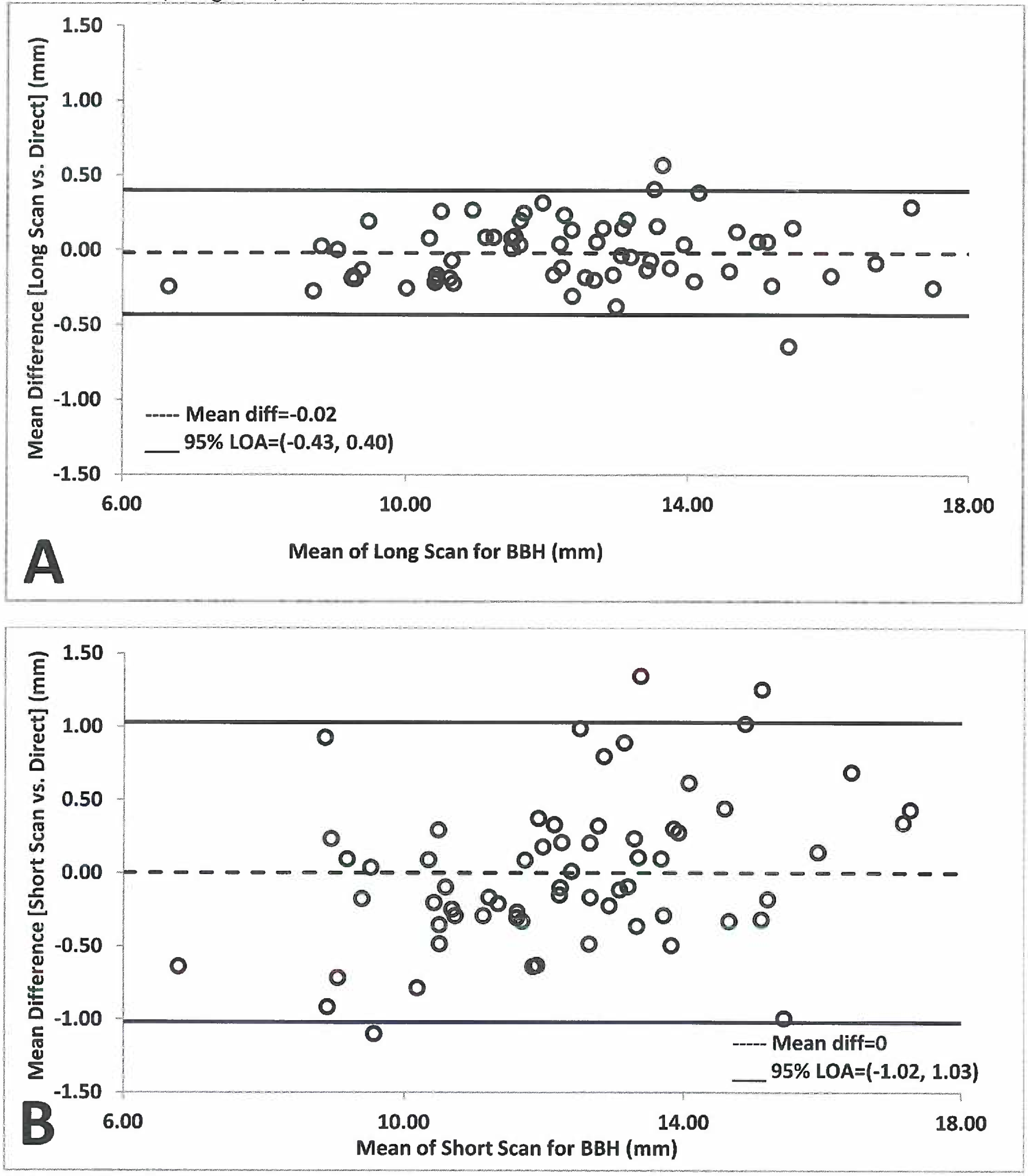
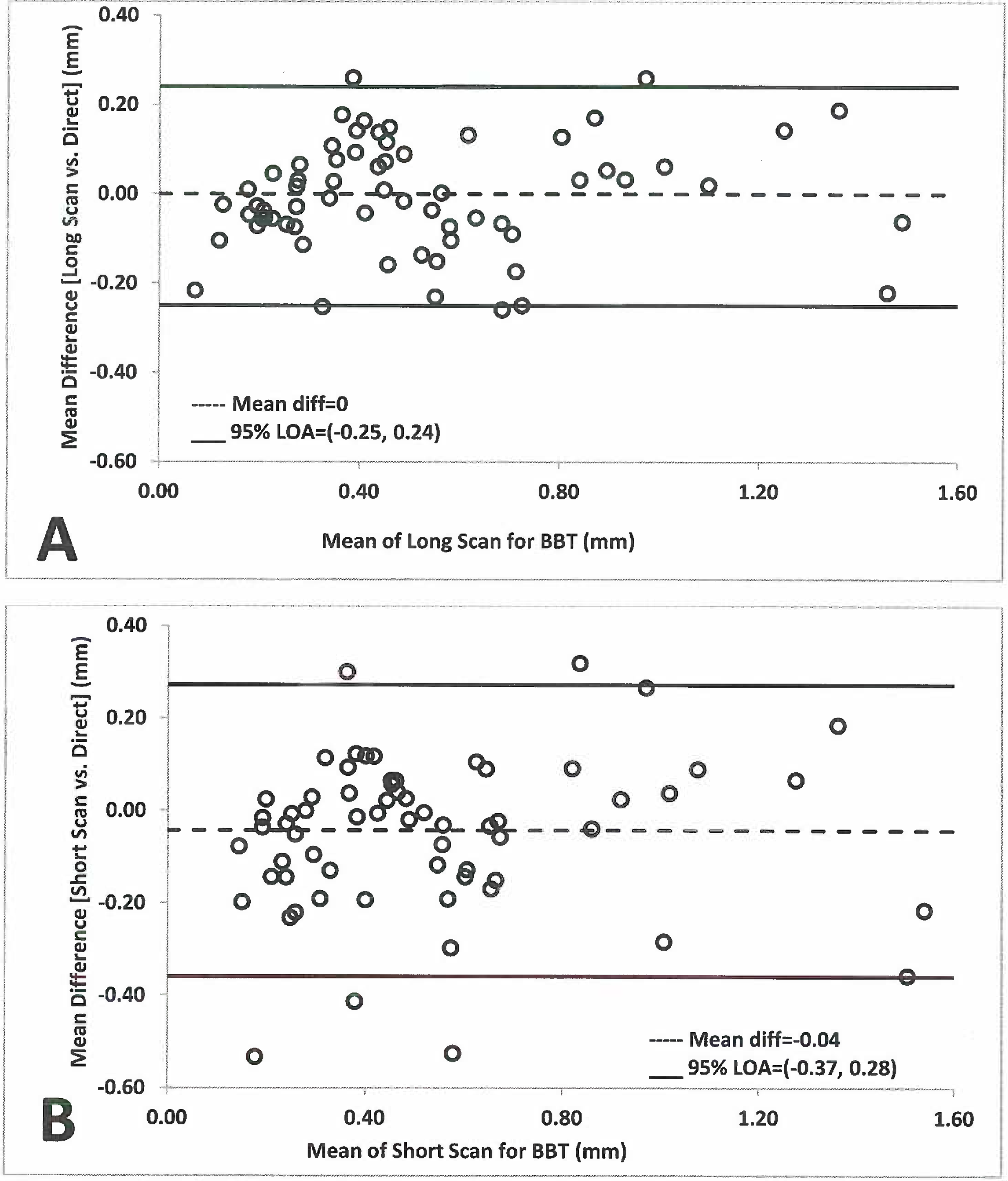


Figure 4. Bland-Altman plots portraying the level of agreement between direct BBT and CBCT measurements: **A,** Long Scan; **B,** Short Scan.



COMPREHENSIVE LITERATURE REVIEW

Orthodontics utilizes radiography to facilitate diagnosis and treatment planning, to monitor treatment progress and effects, and to assess or predict facial growth. Until recently, oral maxillofacial structures have been depicted 2-dimenstionally with traditional radiographic techniques; the diagnostician accepts morphologic asymmetry, magnification, and distortion. With these limitations in mind, recent advances in three-dimensional imaging modalities such as cone beam computed tomography (CBCT), allows practitioners access to rendered images which depict the true anatomy of the patient more accurately. CBCT may facilitate analysis of anatomic structures or planes of space with greater fidelity and provide analysis of structures and spatial planes that were previously inaccessible.

Numerous supposed applications of CBCT exist in every field of dentistry; the investigation of each application must be examined individually. The specific focus of this investigation lies in determining dimensional accuracy of CBCT, when assessing buccal alveolar bone height and thickness.

With the aid of CBCT, diagnosticians are evaluating the characteristics of alveolar bone in a manner previously accessible only through surgical dissection. The ability to characterize alveolar bone proves to be exciting for numerous restorative, periodontal, surgical, and orthodontic procedures. One particular application, which has many orthodontists excited, deals with assessing buccal alveolar bone height and thickness during and following arch expansion therapy. When alveolar bone height and thickness are viewed longitudinally, they may indicate the maintenance or loss of alveolar bone. Alveolar bone quality following orthodontic treatment continues to be a topic of paramount concern for orthodontists and patients, especially considering recent popularity in arch expansion therapies, which many believe may have deleterious effects on the periodontium.

The sequela of excessive arch expansion techniques may include increases in anatomic crown height, buccal cortical plate thinning, fenestrations and dehiscence—all of which are difficult or impossible to assess by traditional radiography and which may present clinically as gingival margin retraction. These adverse effects are thought to occur as a result of displacing teeth through or removing them from the envelope of the alveolar process. The diagnostic ability to identify patients and treatment mechanics that increase risk for such sequela is a critical component to providing proficient orthodontic therapy and allows the patient the greatest probability of enjoying long-term periodontal health and alignment stability.

As CBCT technology gains broader accessibility and the means of characterizing alveolar bone becomes refined, it is important to investigate its value with respect to perceived risks and benefits including, radiation dose, dimensional accuracy, and improved treatment outcomes. Invariably, certain diagnostic tests will require greater spatial resolution (thereby requiring greater effective radiation doses), while others may provide clinically significant data (lower resolution imaging) while minimizing radiation exposure.

The purpose of this in vitro study of the human craniofacial complex is to investigate the dimensional accuracy and quality of the representation of the buccal alveolar cortical bone by CBCT at multiple imaging parameters; thereby, determining the appropriate effective radiation doses necessary to render diagnostic quality images.

Specific aims are:

1. To compare the effect of different imaging parameters (i.e. voxel dimension, collimation, and scan time) on the dimensional accuracy of measurements obtained from CBCT images of human buccal alveolar bone height and thickness compared to actual measurements

acquired from intact human cadaver specimens, from the precise sites of interest. Further statistical analysis will compare values recorded from the maxilla and mandible as well as from posterior and anterior regions.

Null hypothesis states altered imaging parameters will have no effect on the accuracy of the measurements made from the CBCT scans, for all locations and parameters.

Three-Dimensional Imaging

More than ever, computed tomography (CT) is being utilized frequently in dentistry and in orthodontics specifically. Because the technology allows three-dimensional analysis and provides quality images of high contrasting structures (e.g., teeth and bone), conventional CT has been used to evaluate such diverse entities as the temporomandibular joint[1], osseous pathology[2], craniofacial deformities or asymmetries [3], and preoperative implant positioning[4]. However, drawbacks including cost, equipment size, and risks associated with relatively high radiation doses have made conventional CT impractical for many dental applications. More recently, lower cost and lower dose cone-beam computed tomography (CBCT) has been introduced for head and neck applications, eliminating or reducing many of the disadvantages of conventional CT technology.

Conventional Computed Tomography

Conventional CT scanners acquire data from a patient in the supine position using a thin fan-shaped radiographic beam in multiple axial slices. Once acquired, the slices must be arranged in the correct order and orientation to construct a three-dimensional volume from which subsequent reoriented slices can be made. Assembly of the image involves visual and geometric correction of the raw, or basis, images and a final application of a reconstruction algorithm. The resulting three-dimensional image is composed of voxels (a combination of the terms *volumetric* and *pixel*) defined by their height, width, and thickness. Depending on the distance between slices at acquisition, the voxels comprising a conventional CT scan can be nonisotropic (not identical in all planes) and measurement precision compromised[5]. Although recent advances have shortened acquisition time and radiation dose, these numbers still compare unfavorably to CBCT technology.

Cone-Beam Computed Tomography

CBCT uses a single rotation of 180° or more of the x-ray source and a reciprocating detector about a seated subject to generate a scan of the entire field of interest. The field of view depends primarily on the detector size, beam projection, and selected collimation. Predictably, a larger field of view exposes the subject to a larger radiation dose[6]. Additionally, the number of raw projection images from which the composite image is constructed depends on the frame rate and exposure cycle. Higher frame rates provide more information from which to construct the image, but also decrease the signal-to-noise ratio and increase radiation exposure to the subject[5]. However, in comparison to a conventional CT scan, CBCT exhibits significant dose reduction, decreased by almost an order of ten[7]. Also in contrast to conventional CT technology, CBCT voxels are isotropic, identical in length in all three dimensions.

Other advantages of CBCT technology in addition to a variable collimation, reduced radiation, and voxel isotropy include high speed scanning (completed in as little as 10 seconds), real-time analysis and enhancement (i.e., reformatting images or realigning slices), unique display modes (oblique or nonorthogonal orientations including panoramic images), and submillimeter resolution as small as 0.07-0.25 mm[5].

CBCT Applications

These improved features have given rise to multiple orthodontic applications unique to CBCT imaging. In addition to deriving traditional orthodontic views (e.g., lateral cephalograms, panoramic radiographs) from CBCT data, there exist multiple indications for the use of three-dimensional imaging in orthodontics:

- One can obtain cross-sectional views of hard and soft tissues without superimpositions, allowing improved location of anatomic landmarks used in cephalometric analyses[8].
- CBCT allows for the assessment of treatment outcomes and different patterns of bone modeling following orthognathic surgery. The location, magnitude, and direction of mandibular displacement can be clearly visualized and quantified, as can different patterns of ramus and condylar remodeling[9,10].
- Imaging of impacted teeth allows one to determine the follicular size, inclination, buccolingual position, amount of bone covering, and proximity to adjacent roots in addition to local anatomic considerations and overall dental development[11,12].
- Examination of facial asymmetries, soft tissue, and the airway in three dimensions is made possible, including measuring the cross-sectional area, volume, and shape of the pharynx to aid diagnosis of obstructive sleep apnea[13]. Sagittal cross-sections derived from lateral cephalograms can be misleading or insufficient as the pharynx is often more elliptical than round in the anterior-posterior dimension.
- The determination of mesiodistal root angulation can be made more accurately from CBCT images than conventional panoramic images[14]. Additionally, resorption on buccal and lingual tooth surfaces not captured by conventional radiographs can be adequately visualized.
- Hard-tissue changes resulting from rapid maxillary expansion can be evaluated in three dimensions[15]. This information may also be used to screen patients under consideration for rapid maxillary expansion for risks factors predisposing them to unfavorable bony changes.

– Objective and quantitative evaluations of dental and bony changes as a consequence of specific orthodontic treatment systems are attainable with pre- and post-treatment CBCT images, including alterations in arch width, incisor proclination, buccal bone height, and buccal bone width[16].

Certainly, the unique ability to interact with the data combined with advantages of three-dimensional imaging generates many applications for CBCT in comparison to traditional two- dimensional examinations. As further research is performed, the sphere of CBCT technology continues to expand.

CBCT Dosimetry

Today, many orthodontic offices are obtaining CBCT images as indicated for specific cases while others are substituting CBCT images for all traditional orthodontic views. This practice is expected to grow, raising a valid concern about radiation exposure, particularly for a young patient population considered more sensitive to radiation than adults.

The effects of excessive radiation are well-documented, and there is little doubt that it affects the human body even at low doses[17]. While the exact shape of the dose-response curve is unknown, it is possible a single x-ray could produce a genetic mutation leading to cell death, altered cellular function, or cancer—all termed stochastic effects. Furthermore, there exist thresholds of radiation beyond which predictable, or deterministic, effects such as hair loss and salivary dysfunction occur[17]. Fortunately, radiation doses associated with orthodontic imaging do not approach these deterministic limits. However, it is still imperative to apply strategies for dose reduction to satisfy the As Low As Reasonably Achievable (ALARA) principle in order to minimize the cumulative risks of stochastic effects.

In order to compare the stochastic risks of different imaging modalities and techniques, radiation exposures are often converted to effective doses. Measured in Sieverts (Sv), this unit considers, among other factors, the mean absorbed dose to various organs and tissues, the fraction of that organ or tissue exposed, and their respective radiosensitivities[18]. This permits comparison of the detriment of different exposures caused by various non-uniform imaging examinations such as a full mouth series, a panoramic film, or a CBCT scan to an equivalent detriment produced by a full body dose of radiation[19]. Although dosimetry data is not available for a number of recent CBCT systems, the effective doses for many imaging examinations have been calculated and published in the literature (Table 1). While values vary among different studies, x-ray units, and protocols, the effective dose of a typical digital examination consisting of a panoramic and cephalometric image would range from 7.7 to 25.4 µSv accounting for salivary glands as higher weighted, more radiosensitive organs per the 2007 International Commission on Radiological Protection report. In contrast, the effective dose from a large field-of-view CBCT scan ranges from 77.9 to 1025.4 µSv—a substantial increase. Nonetheless, the calculated probability estimates of cancer induction or other stochastic effects are still very low for each examination: 0.3 to 1.3 X 10^{-6} for a panoramic radiograph, 0.1 to 0.2 X 10^{-6} for a cephalometric, and 3.5-61.5 X 10^{-6} for a full field-of-view CBCT scan[17].

Table 1. Effective doses of common imaging examinations (*Brooks 2009, †White and Pae 2009)

Examination	E (µSv, without salivary glands [1990 ICRP])	E (µSv, with salivary glands [2007 ICRP])
Panoramic (digital)	*2.4-6.2	*5.5-22.0, †9-26
Cephalometric (digital)	*1.6-1.7	*2.2-3.4, †5
Full mouth series		
F-speed or PSP with rectangular collimation		†35
F-speed or PSP with round collimation		†171
D-speed with round collimation		†388
CBCT (full FOV)		
NewTom 9000	*36.3	*77.9
NewTom 3G	*44.5	*58.9, †68
MercuRay	*846.9	*1025.4, †569
i-CAT (9")	*68.7	*104.5
i-CAT (12")	*134.8	*193.4
Conventional CT	*42-657	
Background radiation	*~8 µSv/day, 3000 µSv/year	

PSP=photostimulable phosphor

In addition, there exists many factors both under the control of the operator and specific to the machine that will affect the radiation dose produced by a CBCT system: imaging parameters (kVp, mAs), pulsed or continuous beam, beam filter, amount of rotation, and, as previously mentioned, the FOV and frame rate[17]. Using higher imaging settings increases the information available for reconstruction, but also increases the radiation dose. This may, in effect, create a "prettier" scan, but it has not been found to increase the diagnostic quality[20]. Without a clear answer as to whether the increased information provided by a CBCT justifies its routine use in orthodontics, it is prudent to minimize the radiation exposure to the lowest levels possible while still realizing the benefits of CBCT imaging.

Brown et al[48], using dried skulls, compared linear measurement accuracy of limited projection data CBCT (i-CAT Classic, Imaging Sciences International) measurements of cephalometric landmarks against direct measurement, at three scan settings of different numbers of projections (153, 306, and 612 projections). They found no statistical difference in measurement accuracy between their 3 scan settings (mean difference: 0.44 mm, 0.38 mm, and 0.32 mm, respectively), and likewise suggested a 75% reduction in effective dose with their 153 projection scan, compared to their 612 projection scan. Lennon et al[49] and Durack et al[50] have also demonstrated statistically similar image quality between reduced arc of rotation scans (180°) and complete scans (360°) in the detection of artificial dental periapical lesions.

With parameters facilitating collimation, reduced arc of rotations, variable scan times and projections, it is clear that the term CBCT does not refer to a single imaging protocol. In selecting the appropriate parameters to produce a sufficiently detailed image while minimizing patient radiation exposure, one should consider Pauwels et al[51] effective dose estimations based on 14 CBCT units with variable acquisition settings (FOV size, tube output, and exposure factors). Comparing units and acquisition variables, Pauwels and colleagues[51] demonstrated that for most CBCT devices (at default settings) the effective doses are found in the 20-100 μSv range, with a broader range of 19 to 368 μSv (a 20-fold difference) depending upon the device and acquisition parameters. The greatest variation in effective dose resulted from the size of the FOV[51].

Imaging Sciences International i-CAT 17-19

The i-CAT 17-19 cone beam volumetric tomography and panoramic dental imaging system (i-CAT) is manufactured by Imaging Sciences International and is currently owned and operated by the Department of Oral Pathology and Radiology at Oregon Health and Science University, Portland, Oregon. General technical parameters and settings are displayed in Table 2. According to the operators' manual, the "quality of the images depends on the level and amount of x-ray energy delivered to the tissue," which is conditional to the imaging settings. However, the operating parameters for the i-CAT are generally not modifiable by the user, though both the collimation volume and voxel resolution may be adjusted for each individual scan. Based on these selections, the number of x-ray pulses and scan time are fixed by the software. Because the kVp and mA are fixed for each setting, the amount of x-ray energy, or radiation dose, to the patient is directly proportional to the number of pulses per scan. Generally speaking, the smaller the voxel size, the greater amount of pulses and time needed to capture the image. There exist 43 preset combinations of beam collimation and voxel resolution, with the potential for an infinite amount more if scan volume is adjusted on a case by case basis after a preview image is acquired.

Table 2. 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
Focal spot size	0.5 mm
X-ray beam size	0.5 X 0.5 to 8 X 10 in
Scanning time	4.8-26.9 s
Image Acquisition	180-360° rotation
Image detector	Amorphous silicon flat panel detector
Gray scale	12 bit
Field of view	Variable
Voxel size	0.125-0.4 mm

Though all combinations of the imaging parameters have not been tested, the effective doses for the most popular scanning modes have been calculated. According to the manufacturer, the effective dose for the 26.9 second standard landscape scan with 618 x-ray pulses is 204 μSv using the 2007 ICRP tissue weights. For the equivalent 8.9 second scan with 309 x-ray pulses, the effective dose is halved at 102 μSv. Similarly, the published effective dose for the standard 360° landscape scan with 309 x-ray pulses is 87 μSv[21]. Assuming an effective dose of 24.5 μSv for a typical panoramic dose, a standard i-CAT scan would expose the patient to approximately four times the radiation. Alternatively, the radiation would be in the order of magnitude equal to 11 days of background radiation, and the probability of developing a fatal cancer from the exposure would be roughly four in a million chances[21]. It should be noted that calculated effective dose can vary with the experimental protocol, and it is prudent to evaluate the materials and methods used to arrive at these final calculations.

Dimensional Accuracy

While CBCT imaging is generally regarded as inherently accurate, to date there are limited published reports confirming this assertion. In addition, the published studies have been largely based on the imaging of dry skulls. However, as CBCT popularity has increased so too has the number and clinical applicability of the investigations to reach the literature.

Several studies have evaluated the accuracy of CBCT measurements alongside traditional orthodontic images or conventional CT. Kobayashi et al[22] compared the dimensional accuracy of CBCT to conventional spiral CT for assessing mandibular alveolar ridge height using dry cadaver mandibles. They found significant differences in measurement error between the imaging modalities, with CBCT having a lower mean error, lower maximum error, and lower range of error compared to traditional CT. Additional studies have evaluated CBCT against more traditional orthodontic. Moshiri et al[8] compared the accuracy of linear measurements from lateral cephalometric images derived from CBCT and those taken from traditional lateral cephalograms to direct linear measurements from dry human skulls. CBCT images were accurate ($P \leq 0.05$) for seven of the nine linear measurements whereas traditional lateral cephalograms were accurate for only three of the measurements. Hilgers et al[23] investigated CBCT imaging of temporomandibular joint and mandibular morphology compared to lateral, posteroanterior, and submentovertex cephalograms and found no significant difference for linear measurements from the CBCT images with respect to direct skull measurements, whereas the traditional imaging techniques demonstrated multiple statistically significant differences. Furthermore, the reliability of CBCT measurements was superior, with the variability of measurements from CBCT images significantly lower than that of direct anatomic measurements and cephalometric measurements[23].

Other studies have compared CBCT image accuracy directly to anthropometric measurements made over the entire craniofacial complex, and, though the results are generally affirmative, questions have been raised about the validity of some CBCT measurements. Using measurements of fifty dry skulls immersed in water, Lascala et al[24] found that CBCT values consistently underestimated direct measurements over large distances (e.g., 30 to 100 mm), but these differences (3.43 to 6.59 mm) were significant only for measurements of internal structures at the skull base. A more recent investigation of CBCT dental measurements on dry human skulls revealed a similar trend to underestimate real values, though there was no significant difference for any single measurement with a mean error range of 0.01 to 0.89 mm[25]. Only when multiple measurements were combined to calculate additional distances such as arch length availability did the differences between CBCT and direct skull measurements become significant. Moreover, the investigators proposed two sources of potential systematic error to explain the consistent underestimations by the CBCT measurements: the measurement software itself and the partial volume averaging effect of CBCT. Because CBCT images are reconstructed of voxels, and voxels are a three dimensional volume, it was hypothesized that the measurement software may have measured linear distances from the midpoints of the chosen voxels. If true, half of each voxel potentially would not have been included in the measurement, resulting in a systematic underestimation of anatomic truth. This difference may not be significant over larger distances, but would represent a significant percentage of smaller structures such as teeth or alveolar bone. When this potential voxel-sized error was taken into account and the statistical tests repeated, no significant differences were found for either single or compound measurements. As for the partial volume averaging effect, the authors explain that those voxels at the junction of two objects with differing densities (e.g. bone and soft tissue) could be interpreted as either the less or more dense object depending on the threshold value, as a single voxel can show only one degree of density. High threshold values would favor the less dense object and would generate smaller dimensional measurements for the more dense matter, again resulting in a systematic underestimation.

Another study based on the CBCT measurements of a single skull repeated by multiple operators on four separate occasions demonstrated a mean measurement error of 0.01 mm for twenty-nine distinct linear measurements throughout the craniofacial complex[26]. There was no pattern of under- or overestimation, though five measurement errors were found to be statistically different. All measurement errors were below the known voxel size (0.4 mm) and the authors deemed them to be clinically insignificant, owing the statistically significant differences to the high sensitivity of their study as they focused on the repeated measures of the same specimen.

Recently, investigators have examined the depiction of periodontal structures using CBCT imaging. Using dry human mandibles with artificial bony periodontal defects, Misch et al[27] found no significant difference in linear measurements obtained from bone sounding with a probe, periapical radiography, or CBCT scanning. The unique advantage of CBCT in this study was its ability to detect buccal and lingual defects. The first study of its kind to directly compare osseous CBCT measurements to clinical values from living patients was performed at the University of Texas Health Science Center.

Researchers evaluated the ability of CBCT and intraoral radiographs to assess interproximal alveolar bone level changes in patients following regenerative periodontal therapy. Compared to direct surgical values taken both prior to initial bone grafting and at the six-month reentry surgery, CBCT correlated much more strongly with surgical measurements (r = 0.89-0.95) than intraoral radiographs (r = 0.53-0.67), and narrower confidence intervals suggested better precision of the CBCT measurements[28]. There was no significant difference found between CBCT and surgical measurements of the distance from the cemento-enamel junction to the alveolar crest, the amount of defect fill, or the defect resolution. However, the CBCT significantly underestimated the distance from the cemento-enamel junction to the base of the defect by a mean of 0.5-0.9 mm. Possible explanations for the discrepancy included the overestimation of surgical measurements by an angulated probe or the penetration of the probe into soft cancellous bone at the base of the defect.

Whether taken over a large FOV or focusing on small periodontal defects, on dry skulls or live patients, the published literature favorably compares CBCT measurements to nearly all traditional imaging methods as well as direct. The presence of significant differences in several studies and a trend towards underestimation in others, however, challenges the "inherent accuracy" of all aspects of CBCT imaging. With the large variability of imaging parameters, radiographic units, subjects, and anatomical measurements for the studies described herein, it is difficult to apply these generally promising results broadly to structures not yet investigated. Ultimately, the confidence one has in specific CBCT measurements should be supported by sound research that more closely approximates clinical settings.

Orthodontic-Periodontal Relationship

The relationship between orthodontic techniques and the periodontium has long been recognized, as has its indistinct nature. In fact, the American Association of Orthodontists states in its literature that orthodontic treatment leads to improved periodontal health by such means as facilitating plaque removal and reducing occlusal trauma[29], presumably based on the premise that well-aligned teeth would be easier to maintain and that well-occluding teeth centered in the alveolus would promote a healthier periodontium. Conversely, a recent systematic review of the literature refutes this claim. In truth, the limited evidence that was reviewed suggests a small mean worsening of periodontal status after orthodontic therapy using parameters such as gingival recession, alveolar bone loss, and pocket depth[30]. With more difficult oral hygiene during treatment, the subgingival placement of bands on occasion, and contentious expansion practices, it certainly stands that orthodontic treatment holds some potential for harm as well as for health. However, because of the broad study selection criteria regarding the type of orthodontic treatment (e.g., fixed, removable, extraction, nonextraction), it is impossible to determine the mechanisms by which the intervention caused the effect, beneficial or harmful. Also, the existing body of evidence is incomplete; the review contained only one randomized controlled trial, diverse periodontal outcome measures were assessed, and there existed an admittedly high risk of bias. These details suggest that epidemiologic studies with adequate comparison groups and follow-up time are lacking, as are investigations that focus on specific techniques or appliances such as dentoskeletal expansion to increase arch perimeter. If a clear relationship between orthodontics and the periodontium is to be defined, it must be supported by more strictly controlled, unbiased, and clinically applicable research.

Extraction v. Non-extraction

In 1907, Edward Angle wrote, "The best balance, the best harmony, the best proportions of the mouth in its relations to other features require that there be the full complement of teeth, and that each tooth position shall be made to occupy its normal position—normal occlusion"[31]. Undoubtedly, Angle dominated orthodontic armamentarium, diagnosis, and treatment planning for almost a half century until

Charles Tweed challenged his mentor's nonextraction mantra. Over one hundred years after Angle's assertion, the extraction versus nonextraction debate still lingers—perhaps as the most polarizing orthodontic controversy today. As recently as March of 2009, the president of the AAO appointed an ad hoc committee to develop a request for proposal "calling for research on the topic of short- and long-term periodontal health of patients who have significant, six or more mm, of pre-treatment crowding and undergo non-extraction orthodontic therapy" involving comparisons "between bracket types including self-ligating and ligated appliances and their effect on the periodontium, if any"[32].

Arch Enlargement Techniques

With the current emphasis on nonextraction orthodontics and the increased numbers of adult and periodontal patients seeking orthodontic treatment, there is merit in studying the effects of expansion practices on periodontal health. Nonextraction treatment for the correction of dental crowding often involves arch enlargement procedures. Certainly, transverse expansion and/or proclination of the teeth are valid alternatives to extraction in appropriate cases of crowding, but arch development through these methods often lacks stability and the development of bony dehiscences has been demonstrated[33-36]. Though the development of bony dehiscences alone does not directly produce gingival recession[37-38], it may predispose the patient to sudden recession from plaque-induced inflammation or toothbrush trauma[37,39,40]. Clinically, this has manifested itself as an increased risk of labial gingival recession in patients that have undergone rapid maxillary expansion[41]. Physiologically, as individuals' skeletons mature, dental tipping rather than sutural expansion becomes the more likely response to expansion practices[42], placing the teeth at a higher risk of movement through the envelope of the alveolar process.

Animal Models

Histological research relating to this topic has focused largely on animal models, allowing investigators to visualize the supporting structures directly via dissection. In an adult monkey study, investigators demonstrated labial gingival recession of central incisors coincident with their buccal orthodontic movement through the alveolar process[37]. This degree of gingival displacement was not well-correlated with the presence or initial width of the keratinized gingiva, but rather relied on the movement of the tooth through the alveolar process in conjunction with soft tissue inflammation. Even these predisposing factors, however, did not necessarily ensure loss of connective tissue attachment as all experimentally moved teeth suffered bone loss but only 20% experienced connective tissue attachment loss. Based on these findings, the migration of junctional epithelium and loss of connective attachment do not necessarily occur as the result of apical displacement of the buccal alveolar crest. Whereas gingival recession is accompanied by bone dehiscence, the reverse is not necessarily true.

Similarly, a beagle dog study illustrated that with meticulous plaque control, significant bony dehiscences can be produced by orthodontic forces without concomitant loss of connective tissue attachment[43]. Furthermore, it was shown that the repair of bony dehiscences due to labial movement of incisors can occur if the teeth are moved back and maintained within the alveolus. This repair has also been demonstrated in monkey populations[44]. Conversely, if the teeth are retained in their displaced position, those bony dehiscences produced by facial tooth movement do not regenerate even when the forces are discontinued[43].

The preceding studies provide direct histological evidence that deterioration of underlying periodontal structures is not necessarily reflected in the clinical appearance of the dentition and soft tissue. Additionally, there is evidence in animal models to support the fact that, if unfavorable tooth positions are retained, alveolar bone will not regenerate even in the absence of inflammation. Applied to a human population, these findings emphasize the need to carefully move the teeth within the alveolus to reduce the risk of bone loss during active therapy. In cases where resilient gingival tissues mask buccal bone loss, the orthodontist would be blinded to potentially irreversible hard tissue changes. Histological cross sections are not feasible in human patients and soft tissue reflection is impractical if not potentially damaging. However, CBCT imaging—if proven accurate at this scale—would provide a more complete view of the bony consequences of orthodontic therapy.

Phantom CBCT Studies

A recent study[47], regarding CBCT's image quality and technical capabilities, discussed the theoretical limits of measurement accuracy and spatial resolution at various settings in phantom models. The researchers primary objectives were to evaluate images produced by a commercially available CBCT machine (i-CAT model 9140-0035-000C, Imaging Sciences International, Hatfield, Pa) for measurement and spatial resolution (*i.e.,* the ability to separate 2 objects in close proximity in the image) for all settings and in all dimensions. For the study, 2 phantoms were utilized to evaluate their two main objectives (measurement accuracy and spatial resolution).

The first phantom was custom fabricated from acrylic with embedded chromium spheres (Fig 1) (0.3mm diameter positioned 5mm apart in 3 planes of space), which is used to assess measurement accuracy.

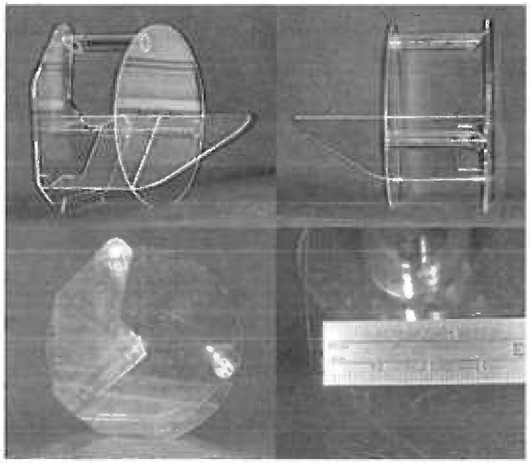


Fig 1. The CIC phantom and 0.3-mm chromium spheres compared with a ruler[47].

The second phantom is a high-contrast line-pair phantom (used to evaluate an image's spatial resolution (Fig 2). The C phantom is made of acrylic and metal plates that are submerged in distilled water. The phantom contains 9 series of 4 plates placed parallel at decreasing distances apart.

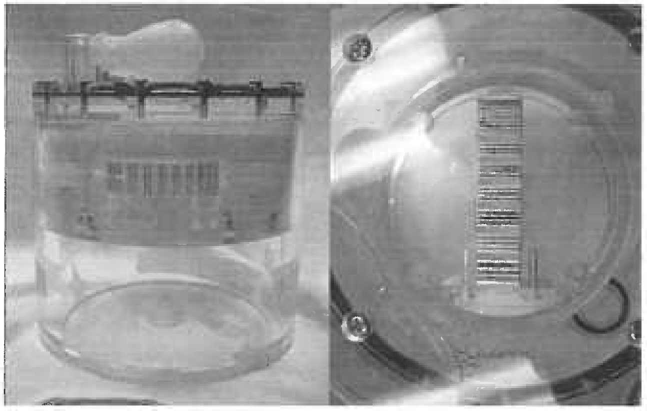


Fig 2. Full view of the C phantom and a top view showing 9 series of metal lines used to assess image resolution[47].

The results of the study suggest that spatial resolution was lower at faster scan times and larger voxel sizes—as anticipated. They demonstrated that linear measurements greater than 0.86 mm from CBCT machines (0.4 mm voxel) are accurate to within 0.1 mm; however; due to the technical limits of the machines (a minimum spatial resolution range of 0.622 mm - 0.860 mm), measuring the distance between 2 objects closer than this range may be futile, since the machine would not be able to detect 2 separate objects that close together.

Their methodology determined to set the theoretical limits of the machine, they utilized phantoms which are stationary and possessed metal markers which yielded high-contrast images, when visualized in relation to a backdrop possessing an absence of adjacent structures. Clinical use of CBCT with long scan times (upward of 40 seconds) in moving patients with surrounding soft tissue, may be disadvantageous due to increased radiation exposure and possible patient movement (which may negate the desirable increase spatial resolution advantages expected with high resolution scans).

More recently, research has utilized computed tomography to assess three-dimensional hard tissue treatment outcomes in human subjects. Investigators at Loma Linda University used CBCT images to explore the factors that may affect buccal bone changes of maxillary posterior teeth after rapid maxillary expansion (RME)[15]. Pre-expansion and post-expansion measurements included buccal bone thickness and buccal marginal bone levels in addition to dental dimensions. Results demonstrated a reduction of buccal bone thickness and buccal marginal bone levels in addition to buccal crown tipping as a result of RME—in agreement to similar studies using conventional CT[45]. Additionally, the initial buccal bone thickness displayed significant correlation to post-expansion buccal bone loss in both thickness and height[15]. These conclusions could not have been made using traditional methods of studying RME, namely dental casts or two-dimensional cephalometric radiographs.

Currently, a CBCT evaluation of the Damon System mechanics is ongoing in the Department of Orthodontics at the University of Oklahoma School of Dentistry. The aim of the investigation is "to evaluate the facial bone changes associated with arch expansion and the Damon System" through the use of CBCT imaging[16]. Although positively marketed for, changes to buccal bone height and width in the Damon system have not been reported in the orthodontic literature beyond case reports. Preliminary results from the study have revealed mean decreases in facial bone height and width in nearly all posterior teeth associated with significant arch expansion. Additional research concerning the Damon System utilizing CBCT imaging is forthcoming from the same investigative team.

As stated by Mah and Hatcher[46], in order to improve the "quality, efficiency and accessibility of craniofacial care" there is a great need for "accurate and effective imaging modalities". With the escalation of studies utilizing CBCT to evaluate post-orthodontic periodontal health and subsequently basing conclusions on these measurement, it is important to verify the accuracy of the technique. Other investigations, as previously mentioned, have demonstrated the reliability of CBCT measurements in many dimensions and planes of space, but, to my knowledge, there exists no study verifying the accuracy of alveolar buccal bone measurements performed on human specimens with soft tissue present. The results of these previous CBCT studies focusing on periodontal health are noteworthy and invaluable; if based on accurate measurements, they may well shape the future trends of orthodontic diagnosis and treatment planning. Therefore, 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 human cadaver heads relative to direct measurements acquired after dissection.

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