Accuracy of cone beam computed tomography in measuring alveolar bone height and detecting dehiscences and fenestrations in patients undergoing periodontal surgery

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Accuracy of cone beam computed tomography in measuring alveolar bone height and detecting dehiscences and fenestrations in patients undergoing periodontal surgery

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Abstract

Introduction: Cone-beam computed tomography (CBCT) imaging has provided a multitude of opportunities for examining craniofacial complex morphology, including alveolar bone. However, studies on CBCT accuracy in assessing bone morphology have been limited and most have been conducted with phantoms, dry human skulls, or cadavers. The purpose of this study was to evaluate the accuracy and reliability of CBCT imaging in measuring alveolar buccal bone height (BBH) and in the diagnosis of naturally occurring fenestrations and dehiscences through comparison of the CBCT image and direct *in vivo* measurements. **Methods:** BBH measurements and the diagnosis of a dehiscence or fenestration were recorded from CBCT images [i-CAT® 17-19 unit (Imaging Sciences International, Hatfield, Pennsylvania) with 0.3 mm voxel size. 5 mA, 120 kVp] in standardized radiographic slices. Measurements were recorded using the original viewing setting (OriCBCT BBH) by Dolphin 3D Imaging® (Dolphin Imaging Systems, Chatsworth, CA) software and again after adjusting for optimal viewing density and contrast (AdjCBCT). All measurements were repeated three times by two independent raters. The presence or absence of a buccal bone dehiscence or fenestration was also recorded. These measurements were compared to *in vivo* BBH measurements and dehiscence and fenestration diagnosis on patients undergoing a periodontal flapped surgical procedure. These measurements were taken by two independent raters. **Results:** Inter-rater reliability was very high with all measurement Pearson correlation coefficients ≥ 0.994. The OriCBCT BBH measurements were statistically different from the direct measurements, whereas the AdjCBCT measurements were not. The OriCBCT and the AdiCBCT were not stastically different from each other. The mean absolute difference was 2.3 ± 1.9 mm for OriCBCT and 1.8 ± 2.0 mm for AdjCBCT. A majority of the CBCT measurements were higher than the corresponding direct values. Agreement was adequate for both CBCT methods, with Pearson correlation coefficients of 0.894 for OriCBCTs and 0.903 for AdjCBCTs. When comparing CBCT viewing methods, the mean absolute difference was 0.7 ± 1.2 mm. The agreement between the two CBCT methods was strong, with a Pearson correlation coefficient of 0.973. For OriCBCTs and AdjCBCTs fenestration sensitivity and specificity was 1.0. The dehiscence sensitivity was also 1 with both CBCT viewing parameters. Dehiscence specificity was 0.5 for the OriCBCT and 0 for the AdjCBCT. **Conclusions:** For the protocol used in this study, CBCT imaging cannot be considered equal to a direct viewing method when determining the presence or absence of alveolar bone. There is a great deal of variability and while CBCT imaging is accurate for some sites, it is inaccurate at other sites.

Introduction

Over the past decade, the use of cone-beam computed technology (CBCT) to image the head and neck region has been advocated. CBCT images do not have the distortion, asymmetry, superimposition, or magnification issues that are seen with traditional radiography (Farman and Scarfe 2009). Newer CBCT machines have been available at a reduced cost and expose the patient to less radiation compared to earlier units. There have been many reports in the literature on the uses of cone-beam computed tomography (CBCT) including viewing of impacted teeth (Nakajima et al 2005; Walker et al 2005), the airway in three dimensions (Ogawa et al 2007), and assessing hard and soft tissue treatment outcomes following orthognathic surgery (Cevidanes et al 2005; Cevidanes et al 2007, Carvalho et al 2010, Ryckman et al 2010), improving cephalometric landmark identification (Moshiri et al 2007), and visualizing tooth and root positions (Peck et al 2007 and Van Elslande et al 2010) and lengths (Sherrard et al 2010).

CBCT imaging provides for the use of isotrophic voxels ranging from 0.07 to 0.4 mm allowing the practitioner to visualize and measure the craniofacial complex in great detail (Farman and Scarfe 2009). In fact, CBCTs have been used in the demonstration of changes in buccal bone dimension following rapid palatal expansion (Rungcharassaeng et al 2007) and dental archwire expansion (Paventy 2008).

Moving teeth buccally within the alveolus has side effects that have been demonstrated in animal studies and histological examination (Allais and Melsen 2003 and Karring et al 1982). Such movements can produce a bony dehiscence of tooth roots, which has little correlation to connective tissue attachment loss. Because of this, the orthodontist could unknowingly cause irreversible hard tissue changes. Bony dehiscences and fenestrations cannot be visualized with 2-

dimensional radiography (Land and Hill 1977 and Rees et al 1971) and the use of CT and CBCT imaging has enabled the practitioner to view buccal and lingual bony defects.

Studies demonstrating CBCT accuracy and image quality for assessing bone morphology have been limited, but have reported a general accuracy (Mengel et al 2005, Mischkowski et al 2007, Loubele et al 2007, Stratemann et al 2008, Misch et al 2006, Baumgaertel et al 2009, Leung et al 2010, Timock et al 2011, Cook et al 2011, Grimard et al 2010). However, very few studies have used an *in vivo* approach to assess CBCT image quality with regard to bone morphology. Radiographic phantoms have been used to demonstrate CBCT accuracy (Marmulla et al 2005 and Ballrick et al 2008). Other studies have used operator creator defects on human skulls with and without radiopaque markers (Mengel et al 2006, Misch et al 2006, Mischkowski et al 2007). Timock et al (2011) and Cook et al (2011) examined buccal bone height and thickness on cadavers. Very few in vivo investigations comparing CBCT bone morphology to a direct visualization gold standard have been completed.

The purpose of this study was to compare the dimensional accuracy of buccal alveolar bone height measurements obtained from cone beam computed tomography (CBCT) images to measurements acquired *in vivo* and to compare the diagnostic accuracy of naturally occurring bony dehiscences and fenestrations viewed on a CBCT scan to a visually confirmed presence or absence *in vivo.*

Material and Methods

Following the approval of the study protocol by the Institutional Review Board, study participants were recruited through the Oregon Health & Science University Periodontal Department. All individuals who met the following inclusion criteria were asked to participate in the study:

(1) Participants were at least 18 years of age with permanent dentition.

(2) Within the last year, participants had a CBCT scan taken as part of his or her dental treatment.

(3) Participants had a periodontal surgery with a full thickness mucoperiosteal flap planned (dental implant placement or sinus lift procedure) as part of his or her dental treatment.

(4) The teeth in the area of the periodontal surgery had an intact clinical crown.

(5) The surgery region was free from pathology.

The following exclusion criteria were applied as well:

(1) Alloy restorations or implants adjacent to the tooth of interest that hindered the viewing of the CBCT image.

(2) Alloy restorations on the tooth of interest that that hindered the viewing of the CBCT image.

Eight individuals were asked to participate in the study and five were able to participate after consenting. Four participants were female and one was a male with ages ranging from 49 – 79 years. Eleven teeth were examined between the five participants.

CBCT Acquisition

The CBCT scans were acquired using an i-CAT® 17-19 CBCT unit (Imaging Sciences International, Hatfield, Pennsylvania) using the technical parameters as specified by the periodontist ordering the scan (Table 1).

CBCT Measurements

Each CBCT scan was stored on a CD-ROM and was opened in Dolphin 3D Imaging® (Dolphin Imaging Systems, Chatsworth, CA) for analysis. CBCT measurements of alveolar buccal bone height (BBH) were completed independently by 2 investigators (M.M. and A. T.). BBH was measured using the original viewing parameters (OriCBCT BBH) set forth by the software and again after the operator manually adjusted for optimal density and contrast for the area of interest (AdjCBCT). The presence of a buccal alveolar dehiscence or fenestration was also recorded. The BBH measurements and the presence of a dehiscence or fenestration were repeated 3 times with a minimum interval of 1 day between assessments and 2 days between taking the CBCT and direct measurements.

The measurements were made in the appropriate sectional slice of 0.5 mm thickness in a darkened room. A standardized orientation protocol that was established by Timock et al (2011) (Figure 1) was used to evaluate the images. The tooth of interest was oriented so that the occlusal plane was parallel to the axial plane and the axial plane was selected to intersect with the crown of the tooth of interest. The coronal and sagittal planes were adjusted to pass through the mesiodistal and buccolingual centers of the crown and root of the tooth of interest (dilacerated apices were ignored). Using the coronal view for posterior teeth and the sagittal view for anterior teeth, BBH was measured from the most incisal (or occlusal) and buccal aspects of the tooth to the most coronal aspect of the buccal alveolar bone crest.

The apical reference point identifying the alveolar crest was dragged apically along the buccal aspect of the alveolar bone to a height that was 3mm greater than the CBCT BBH recording. The buccal bone thickness measurements were made at this level in the axial plane (Fig 1,E)

The presence or absence of a dehiscence or fenestration was recorded. Each tooth root was evaluated in the same sagittal or coronal orientation that was used to determine the BBH. An alveolar defect was determined to be present when there was no cortical bone around the root surface in three consecutive slices. If the alveolar bone height was more than 3.0 mm from the cementoenamel junction, it was classified as a dehiscence (Fig 2). If the defect did not involve the alveolar crest, it was classified as a fenestration (Fig 3). The presence or absence was determined by the majority of the recordings. If a presence was recorded three times and absence was recorded three times, A.T. and M.M. viewed the tooth root together and came to a consensus. This same procedure was repeated after adjusting the image density and contrast until the rater felt the image was most clear.

Direct measurements

During the appointment in which the participant was having a dental implant placement or direct sinus lift procedure performed, BBH measurements were taken with a 4-inch digital caliper (Harbor Freight Tools, Pittsburg, PA). After the alveolar tissue was reflected (mucoperiosteal flap), the buccal bone height of each tooth within the flapped area was measured with a reading to the nearest 0.01 mm using the protocol laid out by Timock et al (2011). One change to the Timock et al protocol involved teeth that had only one adjacent tooth. To measure the BBH of these teeth, the mesiodistal width was measured from the contact of the adjacent tooth to a point that was midway between the facial and lingual boundaries of alveolar bone on the opposite side of the tooth being measured. The center of this mesiodistal plane was then used to measure the incisogingival BBH (Fig 4, D). The presence or absence of a periodontal dehiscence or fenestration was recorded as well. Two examiners independently performed the procedure. Once again, a dehiscence was considered present if the alveolar bone height was more than 3 mm from the cementoenamel junction and a fenestration was recorded as present if the alveolar defect that does not involve the alveolar crest. A photograph was made of the area, including all of the measured teeth and bone.

Statistical Analysis

Intra-rater reliability was assessed using multiple Pearson correlation coefficients. Data from repeated measurements were aggregated before computing other indices of inter-rater reliability and accuracy of the CBCT measurements.

Inter-rater reliability was described by mean differences, mean absolute differences (positive or negative signs ignored), and further analyzed by calculating Pearson correlation coefficients using Excel® for three sets of data: direct measurements of BBH, OriCBCT measurements of BBH, and AdjCBCT measurements of BBH.

Overall measurement accuracy was evaluated using aggregate data from both raters. Comparisons of means, mean differences, and mean absolute differences between the direct and CBCT methods were made. Pearson correlation coefficients were determined to compare the two CBCT methods to each other and to the direct method. Two-tailed paired *t* tests were performed to examine the difference between the direct and CBCT measurement methods and between the two CBCT methods, with a level of significance set to $p \leq 0.05$.

When determining the accuracy of dehiscence and fenestration detection, 2 x 2 contingency tables were created and used to determine sensitivity and specificity when comparing each CBCT method to the direct method.

Results

Intra-rater

Intra-rater reliability for buccal bone height (BBH) CBCT imaging was very high with Pearson correlation coefficients ranging from 0.980-0.999 for both CBCT viewing methods. The mean absolute difference range was 0.15 ± 0.18 mm to 0.63 ± 0.94 mm. Intra-rater agreement for buccal bone thickness (BBT) CBCT imaging was not as high with Pearson correlation coefficients of 0.844-0.958 or the OriCBCT and 0.480-0.864 for the AdjCBCT. The BBT OriCBCT mean absolute difference range was 0.17 ± 0.12 mm to 0.3 ± 0.26 mm and the AdjCBCT mean absolute difference range for BBT was 0.26 ± 0.28 mm to 0.55 ± 0.51 mm.

Inter-rater

Table III displays the descriptive statistics for the agreement between raters for BBH measured directly and from the CBCT images. Pearson correlation coefficients for all of the CBCT measurements were very high, with values ≥ 0.99. The direct measurements also demonstrated excellent inter-rater agreement with a Pearson correlation coefficient of 0.998.

CBCT BBT inter-rater agreement was not as strong as the BBH measurements. BBT OriCBCT PCC was 0.803 with a mean difference of 0.08 ± 0.43 mm and a mean absolute difference of 0.32 ± 0.29 mm. BBT AdjCBCT PPC was higher at 0.905 with a mean difference of -0.11 ± 0.28 mm and an absolute mean difference of 0.22 ± 0.18 mm.

Buccal Bone Height

The direct BBH measurements ranged from 8.6 to 22.5 mm with an average of 13.22 ± 4.23 mm. Table IV shows descriptive statistics for the overall measurement accuracy of the

OriCBCT, and AdjCBCT methods when compared to the direct method. When compared to the direct method, the mean difference was -1.89 ± 2.13 mm for the OriCBCT and was -1.28 ± 2.33 mm for the AdjCBCT. Sixty-eight percent of the time, OriCBCT measurements fell within 4.3 mm of the direct measurements and AdjCBCT measurements fell within 4.5 mm of the direct measurements. The distribution showed 73% of the OriCBCT BBH and 64% of the AdjCBCT BBH measurements were higher than the corresponding direct values. Ignoring the sign difference between the two techniques, the mean absolute difference was 2.09 ± 1.9 mm for OriCBCT and 1.68 ± 1.92 mm for AdjCBCT. Sixty-eight percent of the time, OriCBCT and AdjCBCT measurements fell within 3.8 mm of the direct measurements. Agreement was strong for both CBCT methods, with Pearson correlation coefficients of 0.900 for OriCBCTs and 0.910 for AdjCBCTs (Table IV). The two-tailed paired *t* test demonstrated no significant difference between AdjCBCT ($p= 0.086$) and the direct BBH measurements; however, a significant difference was demonstrated between OriCBCT and the direct BBH measurements ($p = .015$; Table IV).

Table V shows descriptive statistics for the comparison of the CBCT BBH measurements. The mean difference (AdjCBCT- OriCBCT) was -0.61 ±1.22 mm. The distribution shows that 73% of the OriCBCT measurements were greater than the AdjCBCT measurements. A mean absolute difference between methods was 0.67 ± 1.18 mm. The agreement between the two CBCT methods was very strong, with a Pearson correlation coefficient of 0.973. The two-tailed paired *t* test demonstrated no significant difference between OriCBCT and AdjCBCT BBH measurements.

Dehiscence and Fenestration

Table VI summarizes the results of the dehiscence and fenestration detection. Two x two contingency tables were used to analyze the CBCT and direct results (Table VII and Table VIII). For the AdjCBCT, both the sensitivity and specificity for dehiscences and fenestrations was 1. For the OriCBCT the sensitivity for fenestrations and dehiscences was also 1, with a fenestration specificity of 1 and a dehiscence specificity of 0.6 (Table IX). There were two false positive OriCBCT dehiscences.

Buccal Bone Thickness

The mean BBT was 1.48 ± 0.64 mm for the OriCBCT and was 1.14 ± 0.59 mm for the AdjCBCT.

Discussion

The aim of this study was to determine the accuracy of BBH measurements and dehiscence and fenestration detection using CBCT images. Direct measurements were used as the gold standard from which to evaluate the overall CBCT accuracy, thus it was important to have extremely high confidence in the direct measurement values. The mean absolute difference between the two raters' direct BBH measurements was 0.27 ± 0.15 mm, with a Pearson correlation coefficient value of 0.998. These indices demonstrate strong inter-rater reliability for direct measurements and support the appropriateness of the technique employed, creating a reliable standard from which to judge the CBCT measurements.

The OriCBCT values for inter-rater reliability showed an absolute difference of 0.48 ± 0.26 mm. The AdjCBCT inter-rater reliability was closer to one voxel size with a mean absolute difference of 0.35 ± 0.36 mm. Previous studies have shown varying degrees of inter-rater reliability. Suomalainen et al (2008) demonstrated almost perfect interclass correlations of 0.999 when measuring the cross-sectional height and thickness of mandibles; whereas Kamburogle et al (2009) reported varying interclass coefficients from 0.84 to 0.97 when measuring the same dimensions as Sumalainen et al. Cook et al (2011) reported BBH ICC of 0.97-0.99 and buccal bone thickness (BBT) ICC of 0.88-0.94. In 2011 Timock et al as reported inter-rater correlations of 0.98 for CBCT BBH measurements and buccal bone thickness correlations were reported to be ≥0.97. The current study showed comparable high inter-rater reliability by means of Pearson correlation coefficients of 0.994 and 0.996 for OriCBCT BBH and AdjCBCT BBH measurements, respectively.

Assessment of overall buccal bone height measurement accuracy showed that the mean differences between direct and CBCT measurements were -1.89 ± 2.13 mm and -1.28 ± 2.23 mm for OriCBCT and AdjCBCT respectively. The mean absolute differences were 2.09 ± 1.9 mm (OriCBCT) and 1.68 ± 1.92 mm (AdjCBCT). The Pearson correlation coefficient was 0.900 for OriCBCT and 0.910 for the AdjCBCT, indicating a good agreement between the direct and the CBCT measurements. The AdjCBCT BBH measurements were between 0.5 and 1mm closer to the direct measurements than the OriCBCT measurements, however this difference was not statically significant (Figure V). The variability in the data between the two CBCT measurements remained the same, indicating that for some teeth the CBCT scans were very accurate and for others the CBCT BBH measurements were not accurate, regardless of what viewing parameters were used (Figures V and VI). These measurement errors and standard deviations are higher than all previously reported studies. For example, Mengel et al in 2005 compared buccal bone height measurements using dry pig and human mandibles. A 0.19 ± 0.11 mm difference was found between the BBH measurement of the osseous created defects made directly on the mandibles versus with CBCT scans. Mischkowski et al (2007) used fabricated holes on dry skulls with gutta percha markers and found a mean absolute difference of 0.26 ± 0.18 mm when comparing direct and CBCT distances between the makers. Also with gutta percha markers and dry mandibles, Loubele et al (2007) demonstrated an underestimation of buccolingual mandibular thickness of 0.23 ± 0.49 mm when compared to direct measurements. Stratemann et al compared direct and CBCT craniofacial distances on dry skulls with chromium markers and found mean absolute differences of 0.07 ± 0.41 mm and 0.00 ± 0.22 mm for the two machines tested.

Other studies have utilized dry skulls without markers. Misch et al (2006) demonstrated a difference of 0.41 ± 1.19 mm when comparing the BBH of osseous created defects on dry skulls and CBCTs. Baumgaertel et al (2009) compared dentition measurements (overjet, overbite, arch length, and arch width) on dry skulls and a Mercuray CBCT image and found the mean differences to range from 0.01 to 0.89 mm. Leung et al (2010) utilized natural dentition of dry skulls to compare direct and CBCT BBH measurements and found a difference of 0.2 ± 1.0 mm and absolute difference of 0.6 ± 0.8 mm.

Timock et al (2011) and Cook et al (2011) measured BBH and BBT on embalmed cadaver heads; thus incorporating soft tissue into the study of CBCT accuracy. When compared to a direct measurement, Timock et al (2011) found the mean absolute difference in BBH to be 0.30 ± 0.27 mm with a concordance correlation coefficients of 0.98. With a mean absolute difference of 0.41 ± 0.32 mm, Cook demonstrated that decreasing the scan time (26.9 to 4.8 seconds) and increasing the voxel size (0.2 to 0.3 mm) still provides accurate CBCT BBH measurements. Both of these studies produced smaller mean absolute differences and higher correlations than the present study. Sherrard et al (2010) demonstrated similar accuracy, but with a large standard deviation when imaging porcine heads with soft tissue. Mean differences of less than 0.15 mm and 0.30 mm for tooth and root lengths were reported. However, the standard deviations ranged from ±1.71 mm to ± 1.83 mm for tooth and root lengths respectively.

Grimard et al (2010) measured interproximal bony defects at the time of regenerative periodontal surgery and at a later re-entry surgery date. The mean difference between the direct surgical measurements (full thickness flap was performed) and the cone beam volumetric tomography measurements ranged from -0.9 ± 0.8 to 0.1 ± 1.2 mm with r values between 0.89 and 0.95. The results of the current study differ from the previously reported studies because the current study was conducted using live pts and because of the CBCT scanning settings and limited spatial resolution.

A secondary aim of this study was to evaluate CBCT accuracy in detecting buccal alveolar dehiscences and fenestrations. All of the dehiscences and fenestrations were detected with both the OriCBCT and AdjCBCT images. The OriCBCT reported two false dehiscences and no false fenestrations were reported. Fenestration sensitivity and specificity of 1 were reported for both the OriCBCT and AdjCBCT. Dehiscence sensitivity of 1 for both CBCT viewing parameters was reported and an OriCBCT specificity of .5 was reported. Misch et al (2006) used artificially created dehiscences and fenestration on dry pig and human skulls with gutta percha points to aid in landmark identification and Mengel et al (2005) also used artificially created dehiscences and fenestrations on mandibles. Both reported that all dehiscences and fenestrations were detected with CBCT imaging.

Leung et al (2010) looked at over 300 teeth to determine CBCT imaging accuracy and reliability in diagnosing naturally occurring fenestrations and dehiscences. Sensitivities of 0.81 for fenestrations and 0.42 for dehiscences were reported. These are lower than our reported values. Specificity values of 0.81 and 0.95 (fenestrations and dehiscences respectively). Three times more fenestrations were noted on the CBCT than were actually present on the skulls. Our current study did not detect any false positive fenestrations, however we did detect 2 false positive dehiscences. Leung et al (2010) also reported a significant number of false negatives. More than half of the dehiscences present were not detected on the CBCT. This does not correspond with the results with the current study; however, due to the very small sample size of the current study (n=10), the sensitivity and specificity values reported are likely not as reliable as those reported by Leung et al (2010).

Whether measuring BBH or looking for dehiscences and fenestrations on a CBCT, the alveolar bone margin must be identified. Cementum has 45- 50% hydroxyapatite and bone contains approximately 65% hydroxyapatite (Carranza et al 2002), making their densities very similar. Because of the similar densities, CBCT accuracy in detecting the alveolar bone margin is limited, not by voxel size, but by spatial resolution (Leung 2010). Spatial resolution is the ability of the CBCT to detect that there are in fact two objects in close proximity (as opposed to them being one object). This is not to be confused with measurement accuracy which reports how well a CBCT machine detects the distance between two separate objects. Molen et al (2010) suggests that investigations should report a CBCT scan's voxel size and spatial resolution. Many studies have reported linear accuracy to tenths of a millimeter or less, however studies demonstrate spatial resolution values that can be significantly greater than the voxel size. Ideally, spatial resolution should be the same as the voxel size, however, due to noise, scatter, and other factors, this has not been the case.

The spatial resolution of a CBCT machine can be determined using phantoms. Ballrick et al (2008) used phantoms containing 9 series of 4 plates placed parallel to one another at decreasing distances apart to test CBCT spatial resolution. They tested various CBCT settings including field of views ranging from 6- 13 cm, scan times of 10-40 seconds, and voxel sizes varying from 0.2 mm to 0.4 mm. The results suggest that spatial resolution was lower at shorter scan times and larger voxel sizes, which was expected. They demonstrated average spatial resolutions of 0.66 – 0.86 mm for the CBCT machine tested. This same study reported the mean absolute error for linear measurements made between the metal plates was less than 0.07 ± 0.05 mm. The current study reported mean BBH liner measurements absolute errors that are significantly greater than this (OriCBCT BBH = 2.3 ± 1.9 mm and AdjCBCT BBH = 1.8 ± 2.0 mm).

The ability to visualize two objects that are close together might also depend on image quality. Scanning parameters, such as milliamperage (mA) and kilovoltage (kVp), affect image quality. Miliamperage is the number of X-ray photons and it controls the density or darkness of the image. A large mA indicates that there are more X-ray photons emitted. Contrast is the difference in density between two areas. The difference in tissue density affects the X-ray attenuation which in turn affects the contrast. Contrast is partly controlled by machine kilovoltage (kVp). Kilovoltage controls the energy of the photons. A higher kVp increases the beam quality and the ability of the photons to penetrate the tissue (X-ray energy; Fosbinder and Orth 2012).

The effect of mA on image quality has been studied extensively and Haga et al (1981) reports a loss of low contrast resolution when lower mA setting are used. Misch et al (2006) and Pinsky et al (2006) reported that all operator created dehiscences and fenestrations were detectable and used 47.7 mA, 120 kVp, 20 second and 98 mA, 120 kVp, and 20 second scaning parameters respectively. Our scan settings were all 5 mA and 120 kVp. Leung et al (2010) reported less accuracy in detecting bony dehiscences and fenestrations and used scan setting of 110 kVp, 2 mA, 9.6 s, 12 in FOV, and 0.38 mm voxel. Lascala et al (2004) reported a decrease in CBCT accuracy when measuring linear dimensions between anatomic sites marked with metal spheres when settings of 7 mA, 85 kVp, and 70s.

The difficulty in detecting the alveolar bone margin may also be due to the partial volume averaging effect (Scafe 2008, Schultz 1979, Ballrick 2008). This occurs when a voxel lies on an object of two different densities. A voxel reflects the average density of both objects rather than the true density of one object or the other. When the alveolar bone thickness is reduced to a level close to or less than the voxel size, the voxel reflects an average of the bone, periodontal ligament (PDL) space, and cementum. When only a thin layer of alveolar bone is present, the alveolar bone on the CBCT image can become indistinguishable from the adjacent PDL and cementum. With the average thickness of the periodontal being only 0.5 mm (Sun et al 2011), depending on the voxel size, the bone, PDL space, and cementum junction can become blurred. Leung et al (2010) reported that areas with bone less than 0.6 mm thick were seen on CBCT images as areas without bone. They used a 3-D rendering mode with the following scan parameters: 2mA, 9.6 sec, 12 in FOV, and 0.38 mm voxel. Sun et al (2011) measured BBH on pig maxillas directly and with a CBCT image. All of the CBCT BBH measurements were smaller, indicating more bone was present than on the actual maxilla. A bur was then used to reduce the thickness of the alveolar bone 0.5 - 1.5 mm. The BBH was again measured with a CBCT scan and they found that the new CBCT BBH measurements were 0.9-1.2 mm less than the direct measurements.

The current study also evaluated the correlation between BBH measurements and BBT as recorded on the CBCT. The current study did not find a discernable correlation between the BBT and BBH measurements (Figure VII and VIII). The variability that is seen could be due to the variability in the patients. It is also important to note that the BBT measurements were recorded from the CBCT and were not measured directly, which introduces some inaccuracy. There was a good inter-rater agreement for the CBCT BBT measurements (PCC = 0.844-0.958), however the intra-rater reliability was as low as 0.480 for the AdjCBCT, indicating variability in the ability to discern the BBT. With a larger sample size, the variability could be reduced and a correlation between the BBH and BBT may become discernible.

A relatively unique aspect of the current study is that it was conducted *in vivo*. A majority of CBCT studies examining human alveolar bone have relied on data from dry skulls or cadavers. With the use of live individuals we have introduced the effect of cell water content into the accuracy of the CBCT images. Water makes up 80% of the cells in the human body. The presence of water (when compared to a dry skull or cadaver) increases the tissue attenuation of the X-ray photons and the presence of the live soft tissue can also create a range of contrast that can make landmark identification difficult (Ballrick 2008). Slight subject movement during the scan can also negatively affect a CBCT image.

Although an *in vivo* investigation is an improvement to past studies, there are some limitations with this study. First is the sample size. Generally one cannot draw definitive conclusion from a study with a sample size of 11. The use of periodontally compromised individuals is another limitation of the study, as it makes translating clinically relevant results to most patients in an orthodontic practice difficult. A majority of the patients were significantly older than the average orthodontic patient (study participant ages: 79, 70, 77, 67, and 49 years). Half of the current study sample is comprised of post menopausal women. Seeman (2013) reports that there are similar amounts of cortical and trabecular bone loss during the first 10 years after menopause and that after 60 years of age, cortical bone loss dominates. This bone loss and decreased radiodensity can make bony landmark identification more difficult.

It is important to consider the variation in CBCT imaging studies. CBCT imaging machines, acquisition settings (e.g., image detector type, scan time, field of view, and voxel size), and software, both of the CBCT machine and of the program to complete the measurements can all be different. Measurements made in sectional slices must rely on consistent protocols to reproduce the orientation used for direct measurements or to repeat CBCT measurements at different time points. Knowledge of the measurement protocol and imaging parameters and their potential effect on image distortion and spatial resolution is crucial if one is to draw conclusions from multiple studies evaluating CBCT accuracy studies.

Conclusions:

1. Adjusting the density and contrast of a CBCT image tended to improve the ability of the practitioner to accurately detect buccal bone height when compared to the original viewing parameters in Dolphin Imaging, but, not to a statistically significant amount.
2. CBCT imaging, whether in the original viewing parameter, or adjusted for optimal density and contrast, cannot be considered equal to a direct viewing method when determining the presence or absence of alveolar bone. There is a great deal of variability and while CBCT imaging is very accurate for some sites, it is very inaccurate at other sites.
3. For the AdjCBCT, both the sensitivity and specificity for dehiscences and fenestrations was very high. For the OriCBCT the dehiscence and fenestration sensitivity were high and fenestration specificity was high as well. However, OriCBCT dehiscence specificity was low.

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Figure Legends

Fig 1. Illustration of CBCT measurement protocol: "**A**, initial orientation of the image in the 3-dimensional volumetric view; **B**, the axial plane will be adjusted to pass through the crown of the tooth of interest (red arrow); **C**, the coronal and sagittal planes will be oriented to pass through the long axis of the tooth of interest with the sagittal plane oriented perpendicular to the arch form as viewed in the axial plane; **D**, measurement of buccal bone height (green arrow) will be made in the sagittal plane from the incisal edge (or the buccal cusp tip) to the alveolar bone crest" (Timock et al 2011); **E**, To measure BBT, axial plane (yellow line) repositioned to the CBCT BBH plus an additional 3mm; **F**, BBT measurement made (Green arrow) in the axial pane from the root surface to the buccal aspect of the alveolar bone along the orientation of the sagittal plane (red line).

Fig 2. Dehiscence detection protocol: "at least three sequential views (A indicates cement-enamel junction; B, bone level)" (Enhos et al 2012).

Fig 3. Fenestration detection protocol: "at least three sequential views (A indicates bone; B fenestration area/cement of the root)" (Enhos et al 2012).

Fig 4. Illustrations of the direct measurement protocol: **A** and **B**, buccal bone height (green arrow) measured from the incisal edge or the buccal cusp tip to the alveolar crest following the long axis of the tooth; **C**, when a tooth is rotated, the mesiodistal locations for buccal bone height and buccal bone thickness measurements will be determined by bisecting the width between contacts with adjacent teeth (red line) and projecting this point perpendicularly to the crest of the alveolar bone (green dashed line)" (Timock et al 2011); **D**, when a tooth is adjacent to the future implant site, the buccolingual midpoint of the alveolar ridge will be determined, a line perpendicular to this will extend to the present contact point (red line), and a measurement will be made along a line that projects perpendicular to the crest of the alveolar bone (green line).

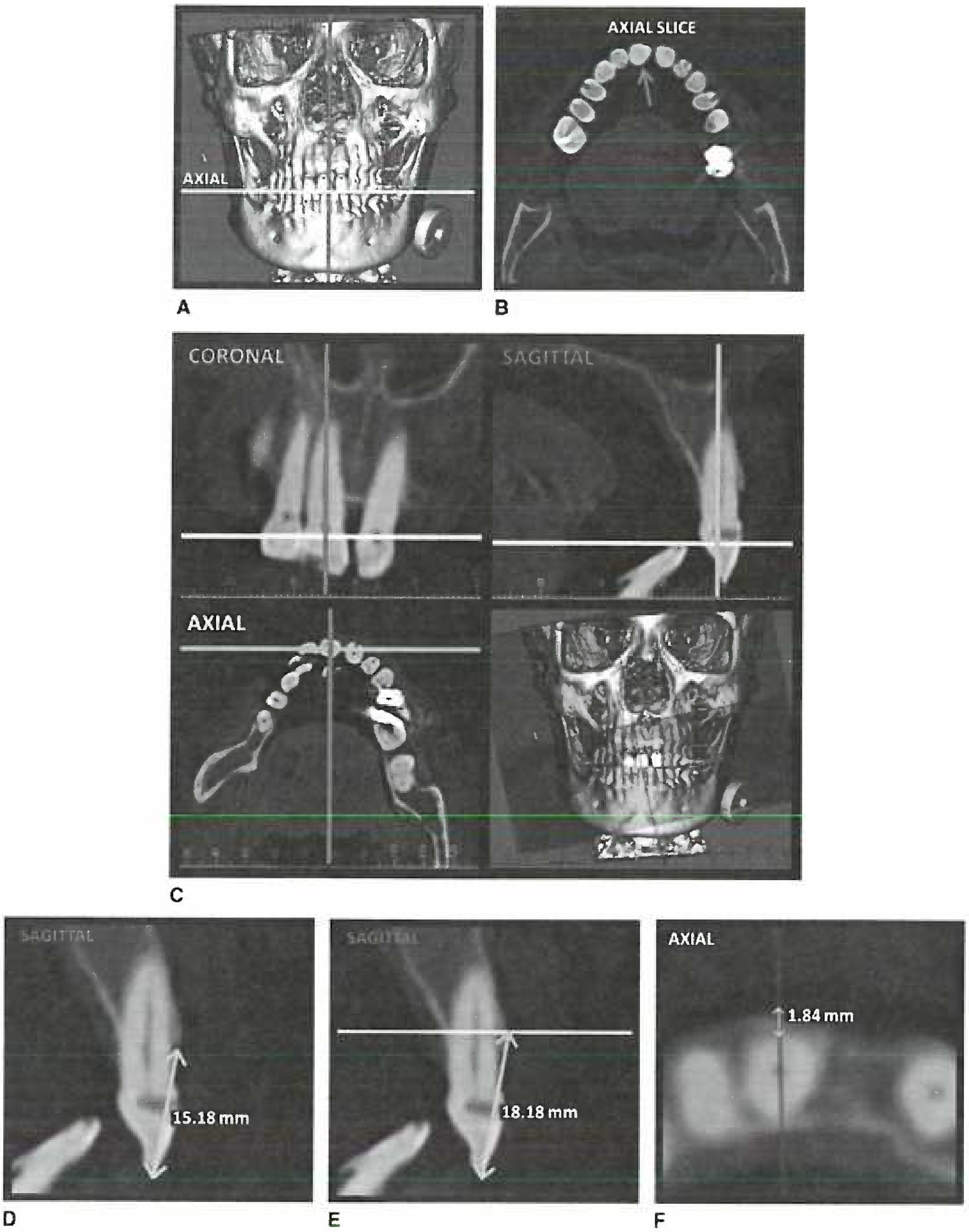
Fig 5. The average buccal bone height measurement's by viewing parameter. Paired two tail *t* – Test statistical significance ($p \leq .05$).

Fig 6. Scatter plot demonstrating the difference between direct and CBCT buccal bone height measurements (Direct BBH – CBCT BBH).

Fig 7. Scatter plot demonstrating the relationship between OriCBCT BBT and buccal bone height measurements (Direct BBH – CBCT BBH).

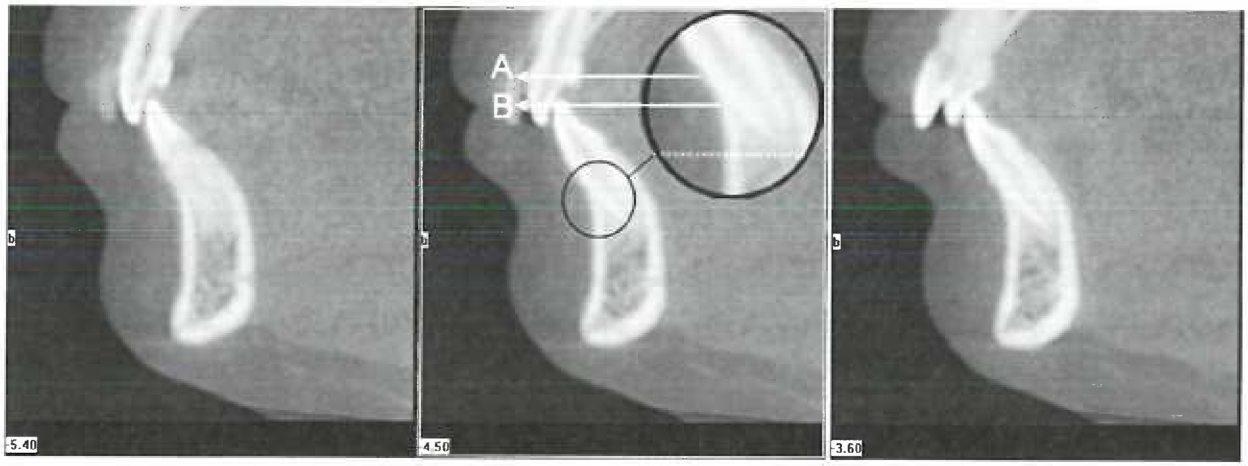
Fig 8. Scatter plot demonstrating the relationship between AdjCBCT BBT and buccal bone height measurements (Direct BBH – CBCT BBH).

Figure 1



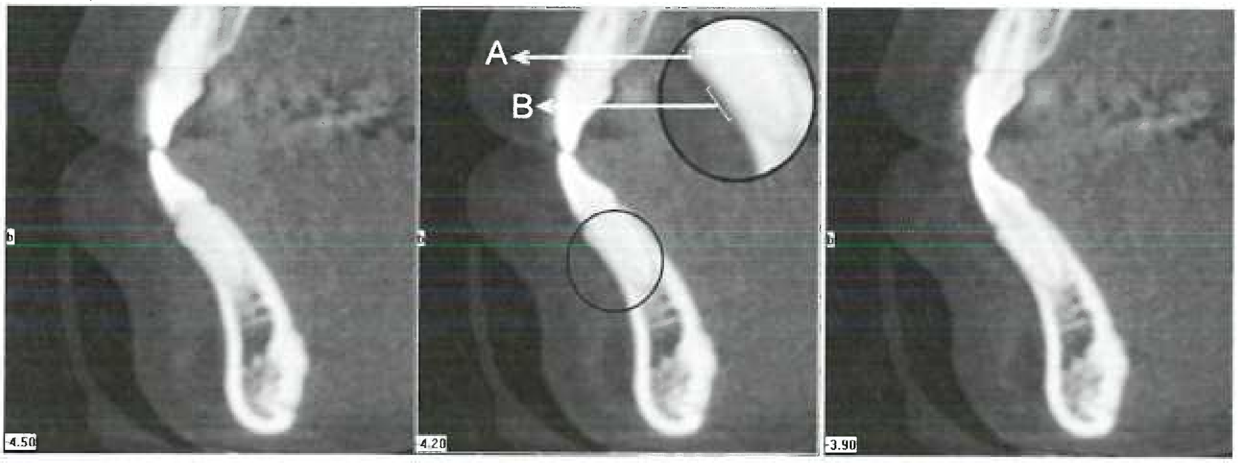
Courtesy of Timock et al 2011

Figure 2



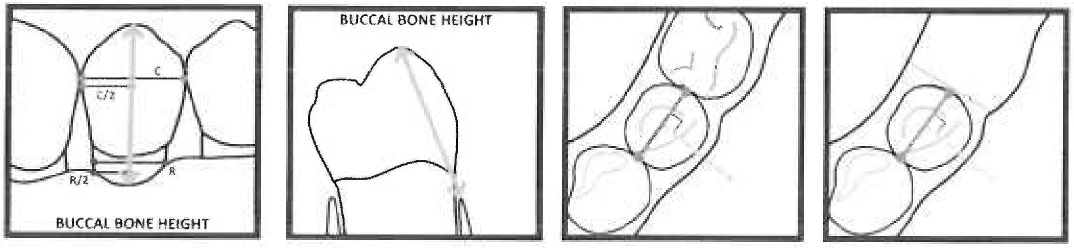
Courtesy of Enhos et al 2012

Figure 3



Courtesy of Enhos et al 2012

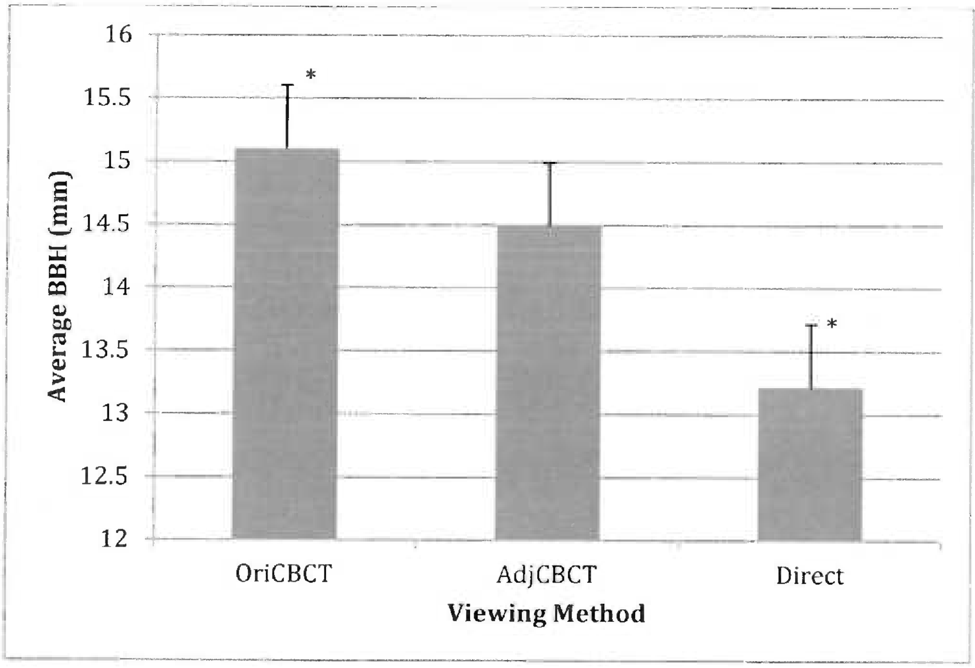
Figure 4



A B C D

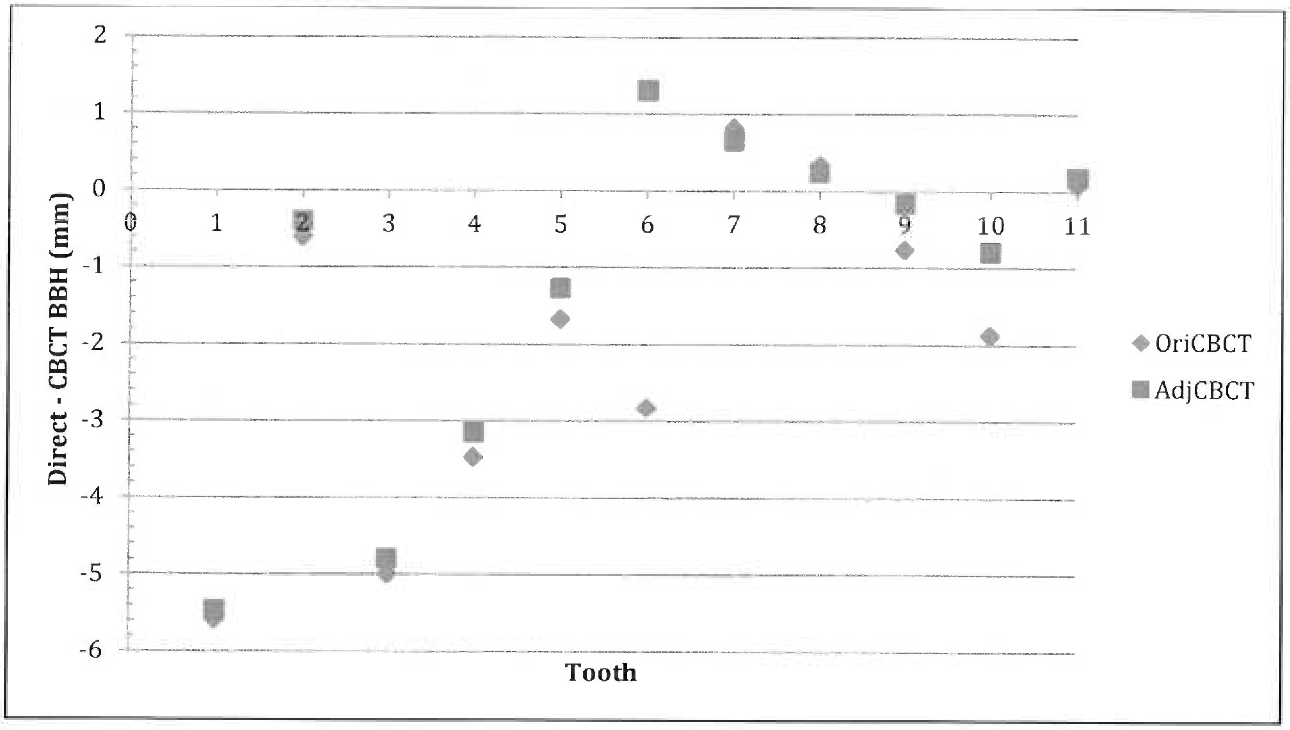
A-C Courtsey of Timock et al 2011

Figure 5



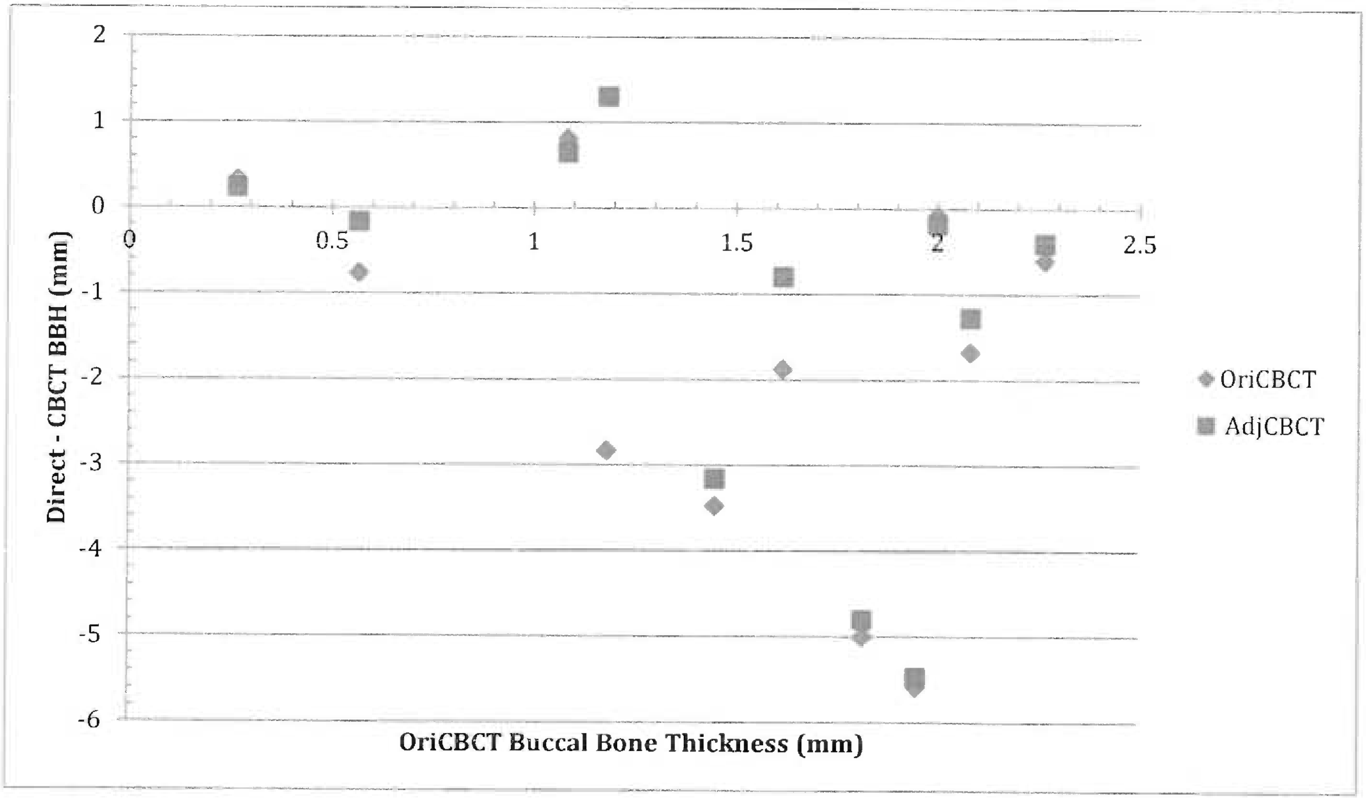
16
15.5
15
14.5
14
13.5
13
12.5
12
Average BBH (mm)
*
*
OriCBCT
AdjCBCT
Direct
Viewing Method

Figure 6



2
1
0
-1
-2
-3
-4
-5
-6
0 1 2 3 4 5 6 7 8 9 10 11
Direct - CBCT BBH (mm)
Tooth
OriCBCT
AdjCBCT

Figure 7



2
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0
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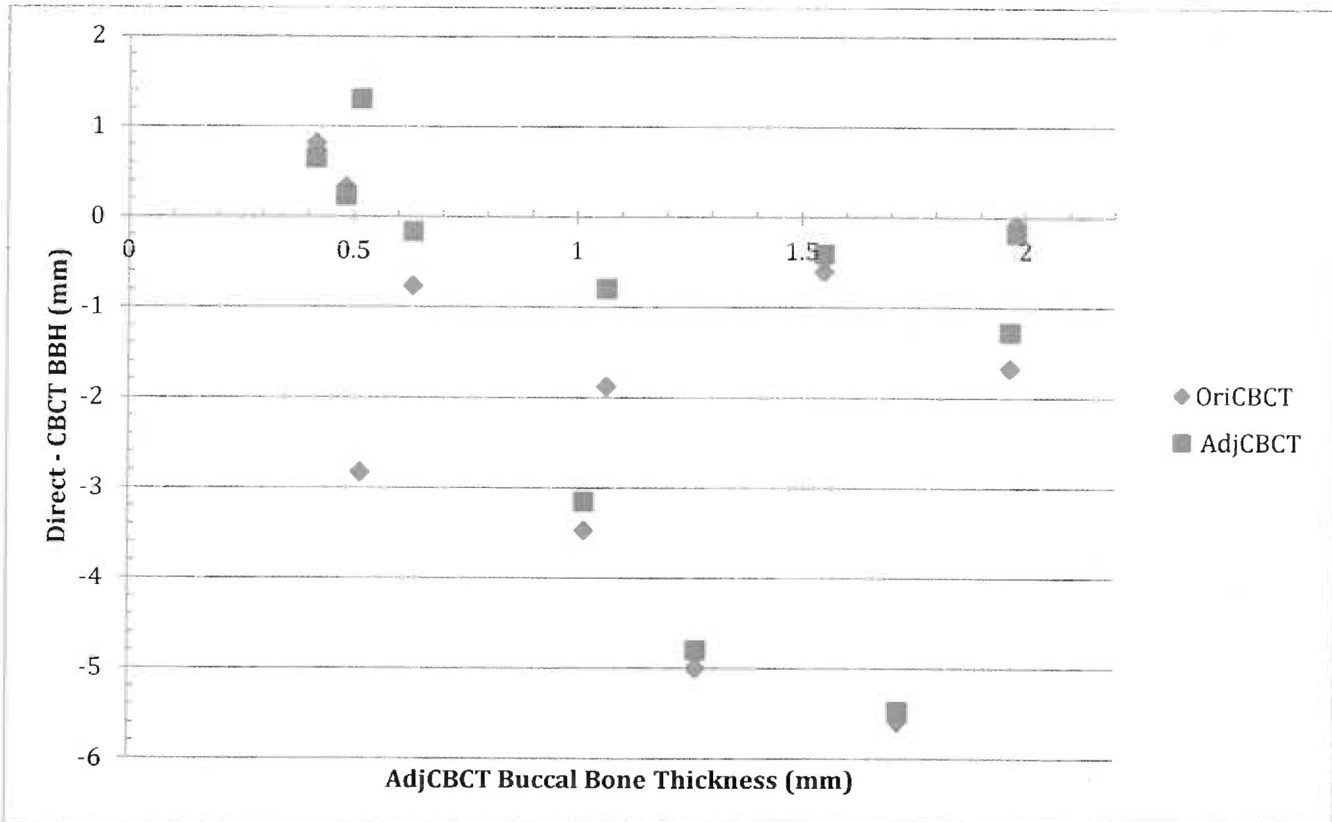
Direct - CBCT BBH (mm)
OriCBCT Buccal Bone Thickness (mm)
OriCBCT
AdjCBCT

Figure 8



2
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1.5
2
Direct - CBCT BBH (mm)
AdjCBCT Buccal Bone Thickness (mm)
OriCBCT
AdjCBCT

Table 1. Technical Parameters and Settings	
Voxel	0.3 mm
Field of View (FOV)	60 cm (for 4 patients) 109 cm (for 1 patient)
kVp	120
mA	5
Exposure Time	4 seconds (s)

Table II. Distribution of teeth examined by tooth type				
Tooth Type	*Maxilla*	*Mandible*	*Total*	
Anterior				
Central Incisor		2	2	
Lateral Incisor		1	1	
Canine	1	3	3	
Anterior total	1	6	7	
Posterior				
First Premolar		3	3	
Second Premolar		1	1	
Posterior total	0	4	4	
Total	1	10	11	

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

	Direct	OriCBCT	AdjCBCT
Mean Diff +/- SD (mm)	-0.16 ± 0.28	0.07 ± 0.56	-0.03 ± 0.51
Mean Abs +/- SD (mm)	0.27 ± 0.15	0.48 ± 0.26	0.35 ± 0.36
PCC	0.998	0.994	0.996

Table IV. Measurement accuracy of CBCT BBH measurements by mean difference (Mean Diff), mean absolute difference (Mean Abs), standard deviation, Pearson correlation coefficient, and p-value

Imaging Parameter	*Difference (Direct -CBCT)* *Mean Diff +/- SD (mm)* *	*Difference (Direct -CBCT)* *Mean ABS +/- SD (mm)*†	*PCC*	*p-value*[ŧ]
Original CBCT	-1.89 ± 2.13	2.09 ± 1.90	0.900	0.015[ŧ]
Adjusted CBCT	-1.28 ± 2.23	1.68 ± 1.92	0.910	0.086

BBH, Buccal bone height

*Mean Difference between each direct and CBCT measurement; † Mean of the absolute difference between each direct and CBCT measurement; Ŧ t-Test: Paired two sample for means with a significance level p≤ 0.05

Table V. Comparison of BBH with multiple CBCT viewing settings by mean difference (Mean Diff), mean absolute difference (Man Abs), standard deviation, Pearson correlation coefficient, and p-value

Difference (AdjCBCT - OriCBCT)	*Difference (AdjCBCT - OriCBCT)*		
*Mean Diff +/- SD (mm) **	*Mean ABS +/- SD (mm)†*	*PCC*	*p-value*
-0.61 ± 1.22	0.67 ± 1.18	0.973	0.130

BBH, Buccal bone height

*Mean Difference between each direct and CBCT measurement; † Mean of the absolute difference between each direct and CBCT measurement; Ŧ t-Test: Paired two sample for means with a significance level $p \leq 0.05$

Table VI. Detection of fenestrations and dehiscences by Direct vs OriCBCT and AdjCBCT methods

	Direct		OriCBCT		AdjCBCT	
Tooth	*Fenestration*	*Dehiscence*	*Fenestration*	*Dehiscence*	*Fenestration*	*Dehiscence*
1		+		+		+
2		+		+		+
3		+		+		+
4		+		+		+
5		+		+		+
6	-	-		+	-	-
7	-	-		+	-	-
8	+		+		+	
9	-	-	-	-	-	-
10		+		+		+
11	-	-	-	-	-	-

+, Presence; - Absence

Table VII. Detection of fenestrations and dehiscences by OriCBCT vs direct methods

	Fenestrations			Dehiscences	
	Direct			Direct	
CBCT	Fen +	Fen -	CBCT	Deh +	Deh -
Fen +	1	0	Deh +	6	2
Fen -	0	10	Deh -	0	3

Fen, Fenestration; *Deh*, dehiscence; +, present; -, absent

Table VIII. Detection of fenestrations and dehiscences by AdjCBCT vs direct methods

	Fenestrations			Dehiscences	
	Direct			Direct	
CBCT	Fen +	Fen -	CBCT	Deh +	Deh -
Fen +	1	0	Deh +	6	0
Fen -	0	10	Deh -	0	5

Fen, Fenestration; *Deh*, dehiscence; +, present; -, absent

Table IX. Sensitivity and specificity of CBCT for detection of fenestrations and dehiscences

	OriCBCT		AdjCBCT	
	Fenestration	Dehiscence	Fenestration	Dehiscence
Sensitivity[a]	1	1	1	1
Specificity[b]	1	0.6	1	1

[a] Sensitivity is the probability of a positive test with the condition (a/ [a + c]). Sensitivity ≥ 0.80 is considered acceptable.

[b]Specificty is the probability of a negative test without the condition (d/ [b + d]). Specificity ≥ 0.80 is considered acceptable.

Literature Review

Introduction

Recently, three-dimensional modalities such as conventional computed tomography (CT) and cone-beam computed tomography (CBCT) have been used by dental practitioners to visualize and measure patient anatomy in three planes of space. Because this technology allows three-dimensional (3D) analysis computed tomography has been used to evaluate diverse entities including the temporomandibular joint (Honda et al 2004), osseous pathology (Fuhrmann et al 1995), craniofacial deformities or asymmetries (Hamada et al 2005), and preoperative implant positioning (Parel and Triplett 2004), among others. CBCT images do not have the distortion, asymmetry, superimposition, or magnification issues that are seen with traditional radiography and they allow accurate measurements in all three planes of space (Farman 2009). However, CBCT has many disadvantages including high machine cost and complexity, large physical size, high radiation dose, and relatively low resolution, which often makes its use impractical for more frequent dental applications. More recently, lower-cost and lower-dose CBCT machines have been introduced for head and neck applications, eliminating or reducing some of the primary disadvantages of conventional CT technology.

Despite the confidence that has been instilled in CBCT imaging, very few studies have assessed the use of CBCT to study the bone morphology *in vivo*. Studies using phantoms, operator created defects, cadavers, and animal models have been used in the past. The ability to accurately characterize alveolar bone in vivo will have interesting consequences for restorative, periodontal, surgical, and orthodontic procedures. Orthodontists are particularly interested in this finding because of the potential for accurately assessing buccal alveolar bone height and thickness during and after orthodontic procedures (i.e. expansion or extractions).

Three-dimensional imaging

The two main differences between conventional CT and CBCT imaging are the type of imaging source-detector complex and the method of data acquisition. A CT X-ray source consists of a high output rotating anode generator and for the CBCT it is a low energy fixed anode tube that is similar to what is used in a dental panoramic machine. CT machines have a fan shaped X-ray beam and the data is recorded on solid-state image detectors which are arranged in a 360° array around the patient. The CBCT has a cone-shaped x-ray beam with a special image intensifier and a solid state sensor or an amorphous silicon plate to capture the image (Figure 1). CT scanners take a series of axial plane slices that are captured as stacked slices or from a continuous spiral motion over the axial plane. Contrary to this, the CBCT rotates around the patient one time (10-30 seconds) (Figure1) (Mah and Hatcher 2004).

During CBCT scans, single exposures are made at certain degree intervals which provide individual two-dimensional (2D) projection images, known as “basis”, “frame,” or “raw” images. These are very similar to a lateral cephalometric radiographic images, each slightly offset from the previous one. The complete series of images is referred to as the “projection data.” The number of images that make up the projection data is determined by frame rate (the number of images acquired per second), the completeness of the trajectory arc, and the speed of rotation. More projection data provide more information to reconstruct a 3D image from the 2D raw images. More projection data also allows for greater spatial and contrast resolution and increases the signal-to-noise ratio, producing smoother images, and reducing metal artifacts. More projection data generally requires a longer scan time and a higher patient radiation dose (Scarfe and Farman 2008).

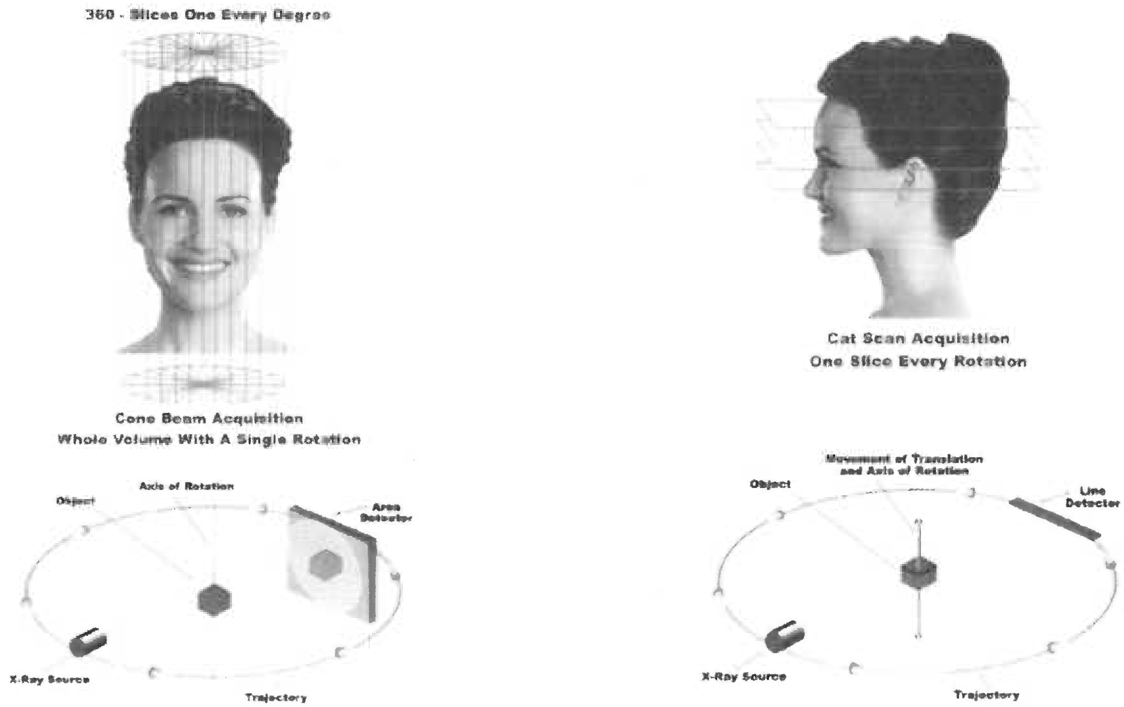

Figure 1. Comparison of fan beam CT and cone beam computed tomography imaging (Mah and Hatcher 2004).

Conventional CT scanners acquire data from a patient in the supine position using a thin fan-shaped radiographic beam in multiple axial slices (Figure 2 A). Once acquired, the slices must be fit together in the correct order and orientation to construct a three-dimensional volume from which subsequent reoriented slices can be made (Farman and Scarfe 2009).

Assembly of both CT and CBCT images involves visual and geometric correction of the raw images and a final application of a reconstruction algorithm. This three-dimensional image is composed of voxels (a combination of the terms *volumetric* and *pixel*), which determine the resolution and detail of the image. A voxel size is defined by its height, width, and thickness. The voxel dimensions are primarily dependent on the pixel size of the area detector for a CBCT and on slice thickness in a conventional CT. CBCT units generally have isotropic voxel resolutions (equal in all three dimensions), while CT units have voxel sizes that are nonisotropic (not equal in dimensions). The nonisotropic CT voxel sizes cause image distortion, as the scans take a series of parallel spirals that have small gaps between them. The computer compensates for the small gaps and hides them with algorithms. However, the gaps can accumulate and create a sizable margin of error (Figure 2A) (Farman and Scarfe 2009).

In contrast, the CBCT x-ray source and reciprocating detector rotate 180° or more around a seated subject to generate a scan of the entire field of interest (Figure 1B). The field of view depends primarily on the detector size, beam projection, and selected collimation. Predictably, a larger field of view (FOV) exposes the subject to a larger radiation dose (Ludlow et al 2006). The number of raw projection images from which the composite image is constructed is dependent 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, on units with a pulsed generator, increase radiation exposure to the subject (Farman and Scarfe 2009). However, in comparison to a conventional CT scan, a CBCT scan exhibits significant dose reduction, up to an order of 10 (Ludlow et al 2003). Other advantages of CBCT technology include high speed scanning (completed in as little as 10 seconds), real-time analysis and enhancement (e.g. reformatting images or realigning slices), unique display modes (oblique or nonorthogonal orientations including panoramic images), and submillimeter resolution as small as 0.25-0.07 mm (Farman and Scarfe 2009).

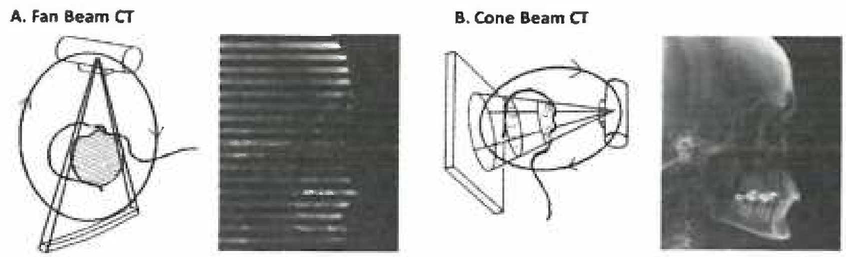

Figure 2. Comparison of fan beam and cone beam computed tomography imaging geometry (Farman and Scarfe 2009)

CBCT Applications

Compared to traditional two-dimensional radiography, CBCT imaging has been used in many new applications because not only does it produce a 3-D image, but the practitioner can directly interact with the image. The expanse of CBCT technology continues to grow as further research is performed. The improved features have given rise to multiple orthodontic and dental applications unique to cone beam 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 all fields of dentistry:

- Impacted Teeth: Imaging of impacted teeth allows one to determine the follicular size, inclination, buccolingual position, amount of bone coverage, and proximity to adjacent roots in addition to local anatomic considerations and overall dental development (Nakajima et al 2005; Walker et al 2005).
- Bone Remodeling: CBCT allows for the assessment of treatment outcomes and different patterns of bone remodeling 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 (Cevidanes et al 2005; Cevidanes et al 2007).

- Orthognathic Surgery Assessment: Three-dimensional assessments of skeletal changes after mandibular advancement surgery (Carvalho et al 2010) as well as other surgeries can now be completed. Soft tissues changes pre and post-surgery can now be compared with three dimensional measurements (Ryckman et al 2010), thus allowing the practitioner to evaluate various treatment outcomes and determine their success or failure.
- Hard and Soft Tissue: Cross-sectional views of hard and soft tissues without superimpositions can be obtained, allowing improved location of anatomic landmarks used in cephalometric analyses (Moshiri et al 2007).
- Soft Tissue Airway: Examination of facial asymmetries, soft tissue, and the airway in three dimensions is made possible with CBCT imaging, including measuring the cross-sectional area, volume, and shape of the pharynx to assist diagnosis of obstructive sleep apnea (Ogawa et al 2007). 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.
- Root and Tooth Length: In 2010, Sherrard et al found that CBCT tooth-length and root-length measurements were not significantly different from the actual lengths, whereas the periapical measurements significantly underestimated root lengths by an average of 2.5mm and overestimated tooth lengths by an average of 2.5mm.
- Root contact evaluation: The determination of mesiodistal root angulation can be made more accurately from CBCT images than from conventional panoramic images (Peck et al 2007). Leuzinger et al (2010) found that orthodontic panoramic radiographs

proved to possess only an 11% diagnostic ability to detect adjacent roots in contact. In 2010, Van Elslande et al also found that the mesiodistal root angulation on a cone beam computed tomographic panoramic-like image is more accurate than when compared to a conventional pan radiograph.

- Resorption and bone loss: Resorption on buccal and lingual tooth surfaces that cannot be captured by conventional radiographs can be adequately visualized with CBCT imaging. 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 (Paventy 2008).
- Orthodontic Temporary Anchorage Devices (TADs) and Dental Implants: CBCT imaging has been used to determine TAD placement sites and dental implant sites. It has been used to visualize adjacent tooth roots and anatomic structures in the area of TAD or dental implant placement as well. For example, the thickest palatal bone was found in the anterior part of the palate, at the suture and in the paramedian areas, but the posterior region is still thick enough to support the use of TADs (Gracco et al 2008).

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 radiographs. This practice is expected to grow, raising a valid concern about radiation exposure, particularly for a young patient population, which is considered to be 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 (Brooks 2009). While the exact shape of the dose-response curve is unknown, it is possible that a single x-ray could produce a nonrepaired mutation of the DNA that can lead to cancer several years in the future. This is termed stochastic effects. Furthermore, there exist thresholds of radiation beyond which predictable, or deterministic, effects such as hair loss and salivary dysfunction occur (Brooks 2009). Fortunately, radiation doses associated with dental 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 the stochastic effects.

Measured doses are collected to produce the *mean tissue absorbed dose* with microgray units (μGy). The percentage of the body exposed is accounted for and the mean tissue absorbed dose is converted to the *equivalent dose* with microsievert units (μSv). However, it must be taken into account that different tissues have more or less sensitivity to radiation. This is done with the *effective dose* (μSv) which is converted from the equivalent dose (Mah and Hatcher 2004). The effective dose is used to compare the stochastic risks of different imaging modalities and techniques. 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 to some extent among different studies, x-ray units, and protocols, the effective dose of a typical digital orthodontic examination consisting of a panoramic and cephalometric image would range from 7.7 to 25.4 μSv with salivary glands being more highly weighted due to its increased radiosensitivity per the 2007 International

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

Commission on Radiological Protection (ICRP) report. In contrast, the effective dose from a large FOV CBCT system ranges from 77.9 to 1025.4 μSv. Despite this substantial increase, 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 radiograph, and 3.5-61.5 x 10^{-6} for a full FOV CBCT (Brooks 2009).

In addition, there exists many factors, both under the control of the operator and inherent 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, FOV, and frame rate (Brooks 2009). Some of these factors create a "prettier" scan, but have not been found to increase the diagnostic quality (Swan 2007).

Without a clear answer as to whether the increased information provided by a CBCT justifies its routine use in orthodontics, or whether the estimated risk is significant enough to be of concern, it is prudent to minimize the radiation exposure to the lowest levels possible while still realizing the benefits of CBCT.

Assuming an effective dose of 24.5 μSv for a typical panoramic dose, a standard i-CAT (CBCT) scan would expose the patient to approximately four times the radiation (Ludlow & Ivanovic, 2008). 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 (Ludlow & Ivanovic, 2008).

CBCT Accuracy

While CBCT imaging is by and large viewed to be inherently accurate, limited published reports on its accuracy and reliability exist. In addition, these 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 investigations in the literature.

In 2008 Ballrick et al published a study on CBCT image quality and technical capabilities. Measurement accuracy and spatial resolution for all settings and in all dimensions were studied (i-CAT model 9140-0035-000C, Imaging Sciences International, Hatfield, Pa). Measurement accuracy is determined by how well a CBCT machine detects the distance between two separate objects, whereas special resolution is the ability of the CBCT to detect that there are in fact two objects in close proximity (as opposed to them being one object).

For the study, 2 phantoms were utilized. Phantoms are stationary and possess metal markers that yield high-contrast images that are visualized in relation to a backdrop that has no adjacent structures present. The first phantom was custom fabricated from acrylic with embedded chromium spheres (Fig 3) (0.3 mm diameter chrome spheres positioned 5 mm apart in 3 planes of space) that were used to assess measurement accuracy. The second phantom was a high-contrast line-pair phantom (used to evaluate an image's spatial resolution) (Fig 4). This 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 (Ballrick et al 2008). The results of the study suggest that spatial resolution was lower at faster scan times and larger voxel sizes, which was expected. They demonstrated that linear measurements greater than 0.86 mm on CBCT machines (0.4 mm voxel size) are accurate to within 0.1 mm.

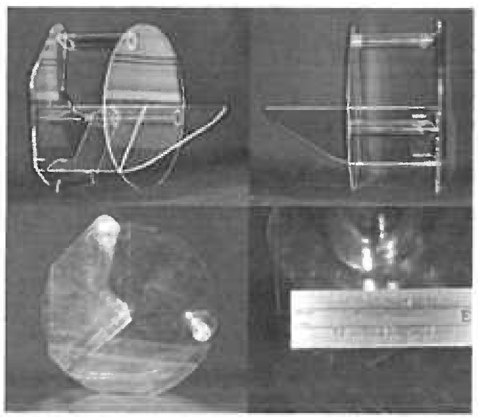

Fig 3. "The CIC phantom viewed at different angles and 0.3-mm spheres compared with a ruler. " (Ballrick et al 2008).

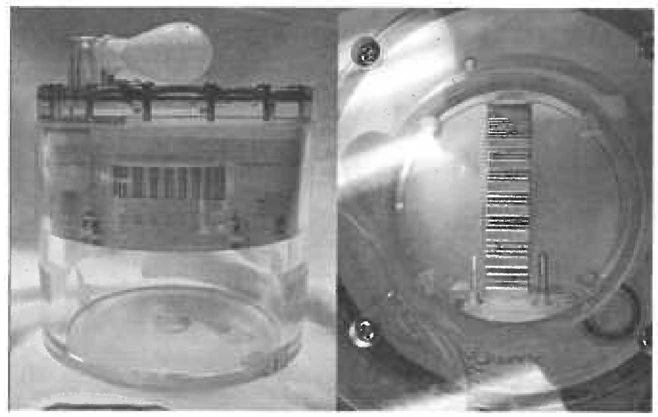

Fig 4. "Full view of the C phantom and a close up view from the top showing the 9 chromium series of metal lines used to assess image resolution" (Ballrick et al 2008).

The phantoms demonstrate the technical limitations of the machine; however, these results cannot be fully applied to patient care. Clinical use of CBCT can require a longer scan time, which can come with a greater risk of movement. This can negate the greater spatial resolution of the longer scan time. Unlike the phantom models, patients also have surrounding soft tissue, creating a range of contrast that can make landmark identification difficult (Ballrick et al 2008).

Several studies have evaluated the accuracy of CBCT measurements against more traditional radiographic images (i.e. panograph, cephalogram, and periapical radiographs). In 2004 Kobayashi et al compared the dimensional accuracy of CBCT to conventional spiral CT in assessing mandibular alveolar ridge height on dry cadaver mandibles. Significant differences were found in the measurement error between the two imaging techniques. The CBCT images were found to have a lower mean error, lower maximum error, and lower range when compared to the traditional CT images.

Other studies have evaluated CBCT against more traditional orthodontic imaging techniques. In 2007 Moshiri et al compared the accuracy of linear measurements taken from lateral cephalometric images derived from a CBCT scan and those taken from traditional lateral cephalograms to direct linear measurements from dry human skulls. The CBCT images were accurate ($P \leq 0.05$) for seven of the nine linear measurements, whereas the traditional lateral cephalograms were accurate for only three of the measurements. Hilgers et al (2005) investigated TMJ and mandibular morphology with CBCT imaging, lateral, posteroanterior, and submentovertex cephalograms and dry human skulls. They found no significant difference between CBCT linear measurements and direct skull measurements, whereas the traditional imaging techniques demonstrated multiple statistically significant differences when compared to the dry skull measurements. Furthermore, the reliability of CBCT measurements was superior, with the variability of measurements from CBCT images being significantly lower than those of the cephalometric measurements (Hilgers et al 2005).

More recently in 2010, Sherrard et al compared the accuracy of measuring tooth lengths and tooth root lengths with CBCT, periapical radiographs, and direct measurement on porcine heads. The following CBCT voxel sizes were used: 0.2 mm, 0.3 mm, and 0.4 mm. CBCT tooth-length and root-length measurements did not differ significantly from the actual lengths whereas, the periapical measurements significantly underestimated root length and overestimated tooth length. They demonstrated that using CBCT to ascertain tooth and root length measurements provides equal to or slightly more accurate results than using periapical radiographs.

Other studies have compared CBCT measurements 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 values. Using measurements of fifty dry skulls immersed in water, Lascala et al (2004) found that CBCT values consistently underestimated direct measurements over large distances (30-100 mm), but these differences were significant only for measurements of internal structures at the skull base and ranged from 3.43 to 6.59 mm. In 2009, Brown et al also found that there was a general trend for CBCT to underestimate linear cephalometric measurements when compared to direct measurements on dry skulls. Another 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 and a mean error range of 0.01 to 0.89 mm (Baumgaertel et al 2009). Only when multiple measurements were combined to calculate additional distances, did the differences between CBCT and direct skull measurements become significant (Baumgaertel et al 2009). The investigators proposed two sources of potential systematic error to explain the consistency of the CBCT underestimation measurements: the measurement software itself and the partial volume

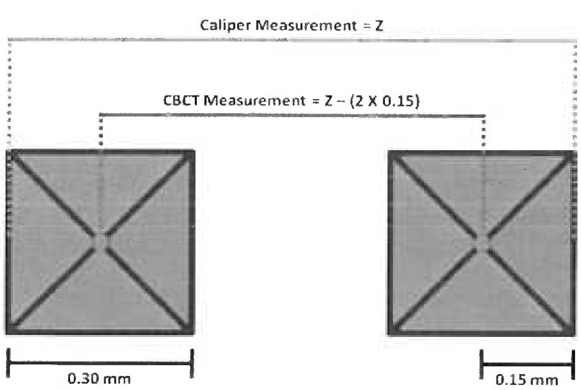

Figure 5. "Description of possible origin of systematic underestimation" (Baumgaertel et al 2009)

averaging effect of CBCT. CBCT images are reconstructed of voxels, which are a three dimensional volume. The investigators suggested that the software measures linear distances from the center of one voxel to the center of the next voxel. If this is the case, half of each voxel would not have been included in the measurement, resulting in a systematic underestimation of anatomic truth (Figure 5). This difference may not be significant over larger distances, but would represent a significant portion of smaller structures such as teeth or the cortical plate. 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 (Baumgaertel et al 2009). As for the second source of error, the partial volume averaging effect, the investigators explain that voxels can only show one degree of density. Voxels that are present at the junction of two objects with differing densities (i.e. bone and soft tissue) can only be interpreted as one density, an average of the two true values (Baumgaertel et al 2009). High threshold values would favor the less dense object and would generate smaller measurements for the more dense matter, again resulting in a systematic underestimation.

Another CBCT measurement study that was based on the repeated measurements of multiple operators demonstrated a mean measurement error of 0.01 mm for twenty-nine distinct linear measurements throughout the craniofacial complex (Berco et al 2009). No pattern of under- or overestimation was found, although, five measurement errors were found to be statistically significantly different. All measurement errors were below the known voxel size (0.4 mm) and the authors deemed them to be clinically insignificant.

Investigators have also used CBCTs to examine the depiction of some periodontal structures. Mengel et al (1991) compared intraoral radiographs, pantograms, computed tomography, and cone beam volumetric tomography (CBVT) to measurements taken on histological sections of surgically created osseous defects in both human and porcine jaws. The CBVT and CT accurately identified all of the defects (buccal lingual, and interproximal), whereas osseous defects on the buccal and lingual surfaces could not be detected with the intraoral radiographs or the pantograms. Another study using dry human mandibles with artificial bony periodontal defects was conducted later by Misch et al (2006). No significant difference in linear measurements obtained from bone sounding with a probe, periapical radiography, or CBCT scanning were found. This study demonstrated the advantage of the CBCT to detect buccal and lingual defects as did the previous study by Mengel et al (1991).

The first study to directly compare osseous CBCT measurements to clinical values from live patients was performed at the University of Texas Health Science Center. Grimard et al (2009) evaluated the ability of CBCT and intraoral radiographs to assess interproximal bone level changes in patients following regenerative periodontal therapy. The CBCT measurements were compared to direct surgical values taken both prior to initial bone grafting and at the six-month reentry surgery. They found that the CBCT measurements correlated much more strongly with surgical measurements ($r = 0.89$-0.95) than intraoral radiographs ($r = 0.53$-0.67). The narrower confidence intervals of the CBCT suggested better precision when compared to the intraoral radiographs. The only significant difference between CBCT and surgical measurements was found when evaluating the height from the CEJ to the base of the interproximal defect. The CBCT measurements significantly underestimated this distance by a mean of 0.5 mm - 0.9 mm. Possible explanations for the discrepancy include the overestimation of surgical measurements due to the angulation of the probe or the penetration of the probe into soft cancellous bone at the base of the defect (Grimard et al 2009).

Whether taken over a large field of view or focusing on small periodontal defects, the published literature favorably compares CBCT measurements to nearly all traditional imaging methods and direct linear measurements of the craniofacial complex. 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 range of imaging parameters, radiographic units, subjects, and linear measurements for the studies described herein, it is difficult to apply these generally promising results broadly to structures not yet investigated singularly. Ultimately, the confidence one has in specific CBCT measurements should be supported by sound research that most closely approximates clinical settings.

Orthodontic – Periodontic Relationship

The relationship between orthodontic techniques and the periodontium has long been recognized, as has its indistinct nature. In fact, literature published by the American Association of Orthodontists (AAO) states that orthodontic treatment leads to improved periodontal health by facilitating plaque removal and reducing occlusal trauma (AAO 2006). This is presumably based on the premise that well-aligned teeth are easier to maintain and that well-occluding teeth that are centered in the alveolus promote a healthier periodontium. Conversely, a 2008 systematic review of the literature refutes this claim. The limited evidence that was reviewed suggests a small mean worsening of periodontal status after orthodontic therapy when evaluating parameters such as gingival recession, alveolar bone loss, and pocket depth (Bollen et al 2008). With more difficult oral hygiene during treatment, the occasional subgingival placement of bands, and controversial expansion practices orthodontic treatment has some potential for harm as well as for health. Due to the broad study selection criteria regarding the type of orthodontic treatment (fixed, removable, extraction, nonextraction, etc.), it is impossible to determine which orthodontic intervention mechanism caused the effect, whether it was beneficial or harmful. Also, the existing body of evidence is incomplete; this systematic review contained only one randomized controlled trial and there existed an admittedly high risk of bias. It was suggested that studies with adequate comparison groups and follow-up time are lacking and that investigations that focus on specific techniques or appliances, such as dentoskeletal expansion to increase arch perimeter, are needed. Arch enlargement, extraction versus non-extraction treatment, and mandibular proclination are all areas of controversy in the orthodontic and periodontal fields. 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.

The extraction versus nonextraction debate has been present since the early 1900s and is perhaps the most polarizing orthodontic controversy today. Literature that can provide conclusive evidence about the periodontal effect of these two treatment modalities is lacking. The president of the AAO appointed an ad hoc committee to develop a request for a 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" (AAO 2009).

Currently, there is great scientific merit in studying the effects of expansion practices on the periodontium as a result of nonextraction treatment because the correction of dental crowding often involves arch enlargement procedures. Transverse posterior tooth expansion and anterior tooth proclination are alternative treatment modalities to extraction in many crowded cases. However, arch development through these methods is often unstable and the development of bony dehiscences has been demonstrated (Ten Hoeve and Mülie 1976; Boyd 1978; Geiger 1980; Little and Riedel 1989). The development of bony dehiscences alone does not directly produce gingival recession (Wennstrom 1996; Allais and Melsen 2003), but it may predispose the patient to recession resulting from plaque-induced inflammation or toothbrush trauma (Wennstrom 1996; Årtun et al 1986; Maynard 1987). This has been demonstrated clinically as an increased risk of labial gingival recession in patients that have undergone rapid maxillary expansion (Graber and Vanarsdall 1994).

Histological research relating to this topic has focused largely on animal models, which have allowed investigators to visualize the supporting structures directly via dissection. In an adult monkey study, investigators demonstrated labial gingival recession on central incisors when they were orthodontically moved through the envelope of the alveolar process (Wennström et al 1987). This amount of gingival recession was not well-correlated with the presence or initial width of the keratinized gingiva, but had a higher correlation with the movement of the tooth out of the alveolar process along with soft tissue inflammation (Wennström et al 1987). While all of the experimentally moved teeth suffered bone loss, only 20% of them demonstrated a loss of connective tissue attachment (Wennström et al 1987). Based on these findings, the migration of junctional epithelium and loss of connective attachment do not necessarily follow the 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 even with meticulous plaque control, significant bony dehiscences can be produced by orthodontic forces without necessarily being accompanied by loss of connective tissue attachment (Karring et al 1982).

These studies provide direct histological evidence that deterioration of underlying periodontal structures is not always reflected in the clinical appearance of the dentition and soft tissue. Soft tissue morphology may play a role in this. In 1969, Ochsenbein and Ross noted a general difference in gingival morphology, with 2 main types: thick and thin. In 1989 Seibert and Lindhe defined these as gingival biotypes and later, Olsson et al (1991, 1993) observed how they may affect the gingival health and therefore our treatment outcomes.

Weisgold (1977) and Seibert and Lindhe (1989) defined a thick biotype as bulky with the marginal gingival being slightly scalloped around short and wide teeth. A thin biotype was defined by the presence of highly scalloped marginal gingiva around slender teeth. Claffey and Shanley (1986) defined tissue biotypes based on thickness. A thin tissue biotype has a gingival thickness of <1.5 mm and a thick tissue biotype has tissue thickness ≥2 mm. Finally, Kan et al (2011) demonstrated that sites with a thick gingival biotype exhibited significantly smaller changes in facial gingival levels than sites with a thin gingival biotype at both1 year after implant surgery and the latest follow-up appointment.

There is also evidence supporting the fact that when retaining unfavorable tooth positions, the alveolar bone does not regenerate even in the absence of inflammation (Karring et al 1982). These findings emphasize the need to carefully move the teeth within the alveolus to decrease the risk of bone loss during active orthodontic therapy. Resilient gingival tissues can mask buccal bone loss and the orthodontist cannot see potentially irreversible hard tissue changes. If CBCT imaging is proved to be accurate at this scale, it would provide a more complete view of the bony consequences of orthodontic therapy. Pre-treatment identification of patients with thin alveolar housing would be beneficial as well, as this can predispose such patients to gingival recession if their lower incisors are proclined (Årtun et al 1987). Knowing if there is a correlation between alveolar gingival thickness and bone thickness could also aid in treatment planning orthodontic cases, treatment planning implant placement, and predicting the esthetic results of both.

Previous Research Completed at OHSU

Previous residents in the OHSU Department of Orthodontics have completed studies on the accuracy and reliability of buccal bone height (BBH) and thickness (BBT) measurements from cone beam computed tomography imaging. Twelve embalmed human cadaver heads were scanned with an i-CAT ® 17-19 (Imaging Science International, Hatfield, Pennsylvania) with a 0.3 mm voxel size. A comparison of the BBH and BBT of the cadaver head measurements and CBCT image measurements was made. Timock et al (2011) found that the intrarater and interrater correlations for all measurements were very high (>0.97) except for the CBCT BBT measurement which was 0.90. The CBCT measurements also did not differ significantly from the direct measurements, however the concordance correlation was higher for the BBH measurements (correlation coefficient of 0.98) than for the BBT (correlation coefficient = 0.86) measurements.

Cook et al (2011) expanded on this project by scanning the same twelve embalmed human cadaver heads [i-CAT ® 17-19 (Imaging Science International, Hatfield, Pennsylvania)] with a 0.2 mm voxel size, 26.9 second (s) scan, and 360° revolution (long scan) and again using a 0.3mm voxel size, 4.8 s, and 180° revolution (short scan). A comparison of the BBH and BBT of the cadaver head measurements and CBCT image measurements at the various scan setting was completed. Statistical similarity was shown for all measurements and neither setting demonstrated an over- or under-estimation tendency. There was a high agreement between the

CBCT measurement methods and the direct measurement method; however, once again, agreement was higher for the BBH than the BBT. Cook et al (2011) concluded that various voxel sizes and scan times can be used to accurately and reliably assess BBH and BBT. The similarity in results between the short scan time and long scan time, favors the use of the shorter scan time to reduce the amount of radiation exposure unless there is a reason that a high resolution image is needed. We wish to continue this line of inquiry by looking at the accuracy of CBCT scans *in vivo*.

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